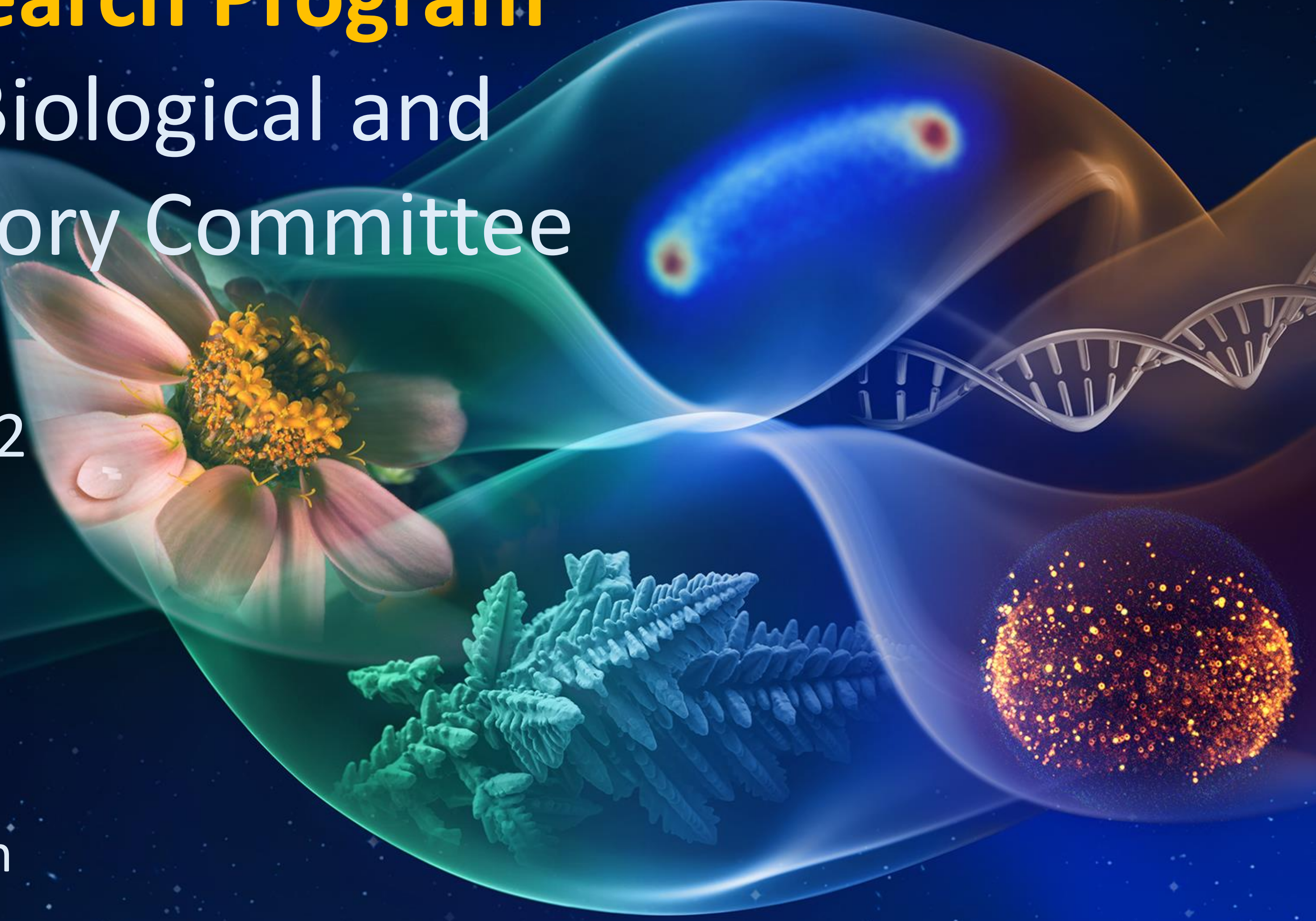
Physical Sciences Research Program

Presentation to the Biological and Physical Sciences Advisory Committee (BPAC)

Nov. 16, 2022



Francis Chiaramonte
Program Scientist for Physical Sciences
Biological and Physical Sciences Division
Science Mission Directorate
NASA HQ

Contributors

- **DeVon Griffin – Physical Sciences Program Manager**
- **Hans Hansen - Physical Sciences Deputy Program Manager**
- **Kelly Bailey – GRC Portfolio Manager**
- **Shawn Reagan - MSFC Portfolio Manager**
- **Mike Sansoucie – Materials Science and Biophysics Lead**
- **David Urban – Science Lead GRC**
- **Dan Dietrich – Combustion Science Lead**
- **John Mcquillen – Fluid Physics Lead**
- **Suman Sinha Ray – Complex Fluids/Soft Matter Lead**

Agenda

- **Overview and Status**
  - Physical Sciences Research Themes
  - Solicitation Plan and Collaborations
  - Impact of current BPS plan
- **Research Activities by Discipline**
- **Future Opportunities**
- **ISS Utilization Schedule**

Overview and Status

BPS Physical Sciences Research Areas

Combustion Science

- Spacecraft fire safety
- Droplets
- Gaseous – premixed and non-premixed
- High pressure/Supercritical
- Solid fuels

Biophysics

- Biological macromolecules
- Biomaterials/Biofilms
- Biological physics
- Biofluids

Fluid Physics

- Adiabatic two-phase flow
- Boiling and condensation
- Capillary flow
- Interfacial phenomena
- Cryogenic propellant storage and transfer

Materials Science

- Glasses and ceramics
- Granular materials
- Metals
- Polymers and organics
- Semiconductors

Fundamental Physics

- Quantum coherence and entanglement
- Quantum interferometry and precision measurements
- Quantum matter
- Many-body systems

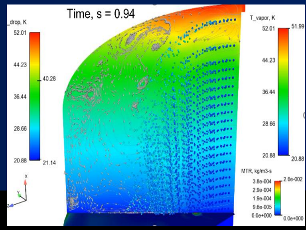
Complex Fluids/ Soft Matter

- Colloids
- Liquid crystals
- Foams
- Polymer solutions
- Granular flows
- Dusty plasma

Physical Sciences Research

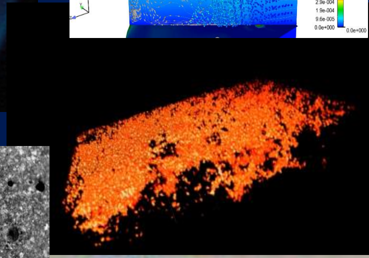
<u>To conduct reduced gravity physical sciences research to advance:</u>

- Scientific Discovery, Space Exploration and Benefit on Earth

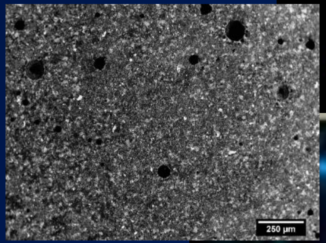


<u>Specifically:</u>

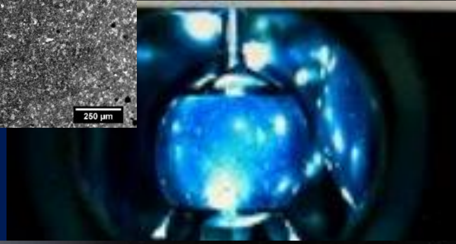
- Identify and understand the underlying mechanisms driving a given phenomena.



- Enable the development of theoretical and numerical models for physical systems.



- Provide scientific understanding to enable technology development for spaceflight systems

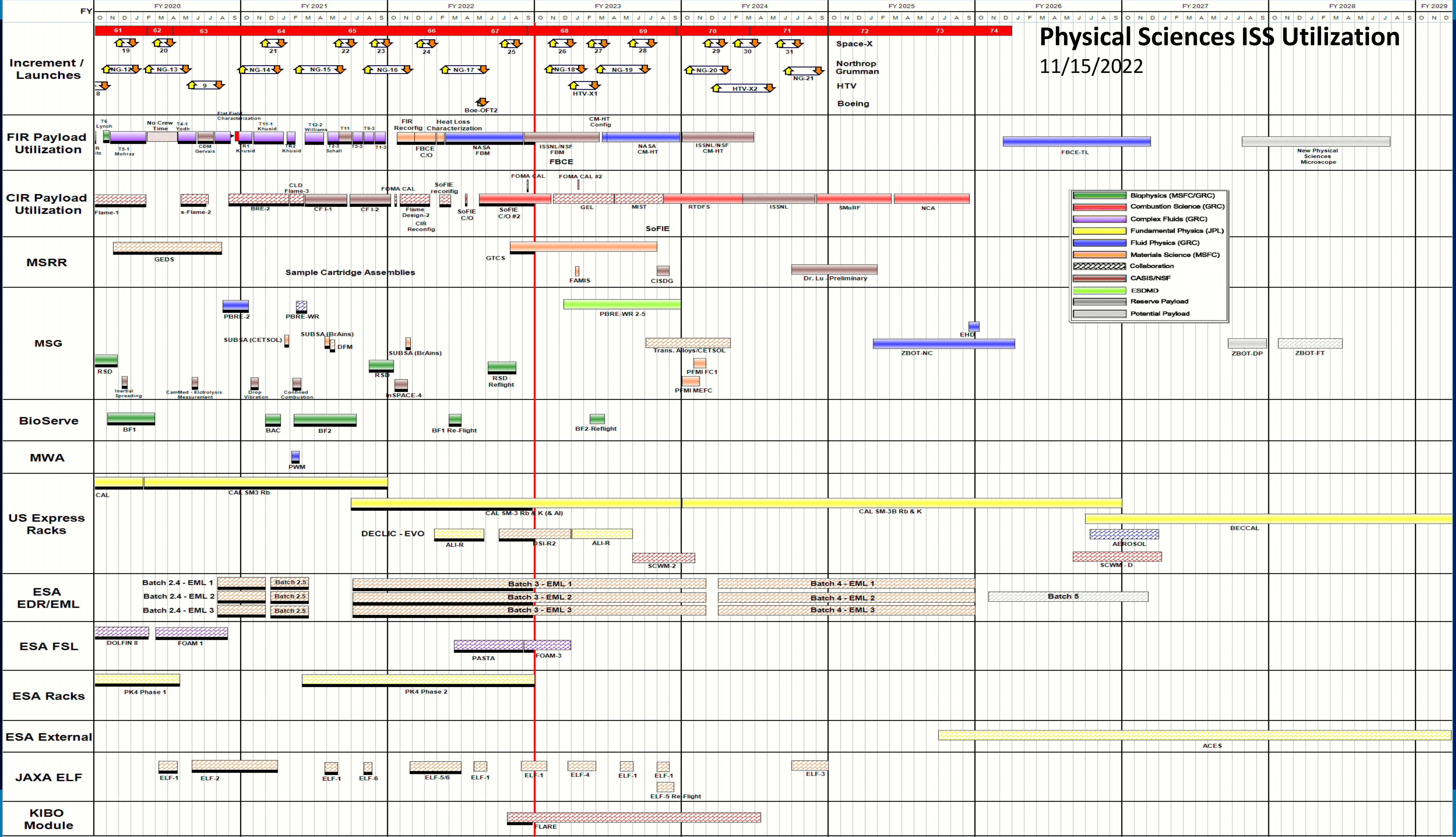


- Transfer the knowledge and technology of space-based research to benefit life on Earth

- Promote open science through the Physical Sciences Informatics System Archive

Physical Sciences ISS Utilization

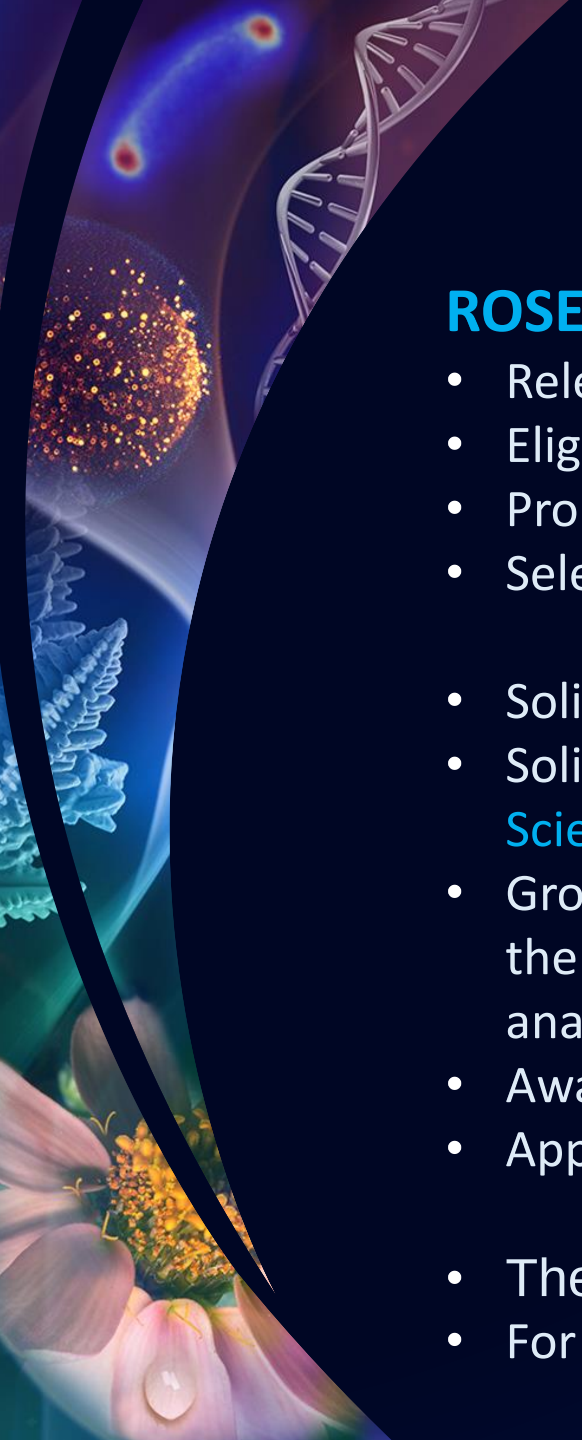
11/15/2022



Agency	Expts	Disciplines	Experiment Acronyms	Notes
Roscosmos	15	Complex Fluids, Combustion, Materials Science	OASIS* CFI, ACME-E-Field, BRE, S-Flame, Flame Design, CLD Flames; SoFIE-Gel, SoFIE-MIST; BRAINS, Diffusion, LCF-Bulk 1,2, LCF-Film 1,2,3	Russian Crew time for Russian investigator access to NASA SLPS experiment
ESA ASI	25	Complex Fluids, Fluid Physics, Fundamental Physics, Materials Combustion	EML: Batch 1-M,K,H, Batch 2-M,K,H, Batch 3-M,K,H, Batch 4-M,K,H; MSRR/MSL: Cetsol, Micast; FOAM, Dolfin, Compgran, PK-4, ACE-T2, ACE-T10, Trans.Alloys, Protein, ACES,SMD (plan) FLEX-ICE-GA	Access to ESA hardware in exchange for NASA crew time and upmass
JAXA	5	Materials Science, Combustion	ELF-US- 1, 2, 3, 4, 5, 6; Flare, FLEX-2J, GCE-US	JAXA furnace & combustion hardware; NASA launch services, cold stowage, etc
CNES	7	Combustion, Fluids, Fund. Physics	HTI-R, ALI-R, DSI-R, HTI-R2, DSI-R2, SCWO and AEROSOL	CNES hardware, NASA upmass, crew time
DLR	3	Fundamental Physics, Fluid Physics	CCF, BECCAL, ZBOT-FT (ground program)	DLR hardware, NASA upmass, crew time
South Korea	2	Complex Fluids	ACE - T1, ACE-T1-3	NASA hardware, S. Korea - Co-I,
Thailand	2	Complex Fluids	LCF – Film 1, 2	NASA hardware, Thailand - Co-Is
ISS National Lab (CASIS)	11	Biophysics, Complex Fluids, Materials Science	ACE-H2, ACE-T1, ACE-2R, ACE-T7, ACE-T6, MICS, LMM Bio-1, LMM Bio-3, RTPCG-1, RTPCG-2, FBCE-reuse	NASA hardware & PIs, ISSNL crew time; MICS and FBCE reuse- ISSNL investigators
NIST	4	Fundamental Physics, Materials	ACES, MICS, MICS-MVP, ELF-US-1	NIST Co-Is (on proposals)
NSF	1	Fundamental Physics	PK-4, FBCE-reuse	NSF funds & selects PIs, SLPS - hardware
Multi Agencies	1	Combustion	Transcritical Combustion (ground program)	SLPS drop tower rig, guest PIs, discussion
NASA - STMD	3	Fluid Physics	ZBOT, ZBOT-NC, ZBOT-AC, ZBOT-FT: *ISS CFM External Experiment*	SLPS Hardware, STMD numerical support *STMD-Hardware, SPLS- Co-I & ISS support*
NASA - AES	6	Fluid Physics, Combustion	PBRE-WR 1 - 6, SCWO	SLPS- core hardware; AES- PI, test articles

OGA and NASA Collaborations/Partnerships

- **ISSNL/NSF**
  - ISSNL and NSF selected two research teams to conduct experiments on NASA BPS's **Flow Boiling and Condensation Experiment**.
  - ISSNL to use the RSD hardware developed by NASA –BPS. Data to be shared.
- **NASA STMD**
  - **Zero Boiloff Tank experiment** series (ZBOT -1, NC and DP) – Modeling support
  - Moon to Mars Planetary Automated Construction Technologies (MMPACT) – in discussion
  - Oscillating Heat Pipes – GSFC Data, numerical simulation, BPS investigation – in discussion
- **NASA – ESDMD**
  - **Packed Bed Reactor Experiment** – Water Purification/Recovery systems
  - SoFIE -Spacecraft Fire Safety/ Materials Flammability
- **NASA BPS – Space Biology**
  - **Plant Water Management** experiments
  - Biofilms experiments – two investigations



Solicitation – Physical Science Informatics (PSI) 2022

ROSES - 2022 PSI Program Element

- Released: September 15, 2022
- Eligible flight and ground investigations: 86
- Proposals Due: January 10, 2023
- Selections: June 2023

- Solicits ground-based research proposals. (Annually)
- Solicits proposals from the following six research areas: Biophysics, Combustion Science, Complex Fluids, Fluid Physics, Fundamental Physics, and Materials Science.
- Ground-based research proposals that present a compelling case on how the data from the PSI system will be used to promote the advancement of further research using data analysis, or numerical and analytical models, or new ground-based experiments.
- Awards: $100,000 in year one and $125,000 in year two.
- Approximately 5 proposals will be selected.

- The program element will be available in NSPIRES as part of ROSES-2022.
- For additional information on the PSI database, visit: https://nasa.gov/PSI

Solicitations 2022 -2028

Combustion

- Supercritical Water Waiting for Decadal Survey Results, one award, 2025 – 2028
- Other topics await Decadal Survey results: Candidates: Transcritical Combustion & Flammability of Materials

Fluids Physics

- Multiphase flow with heat transfer - Three awards are planned. Will be coordinating with Decadal Survey results. Funding 2023 – 2027. Candidate: Oscillating Heat Pipes & other Thermal Management.
- AEROSOL – one award. Coordination with CNES – DECLIC. 2025 -2028

Materials Science

- Four to Five awards planned. Potential areas include, EML Batch 5, Lunar Concrete, microstucture of materials for additive manufacturing, will align with Decadal Survey. Funding 2023 – 2027. Candidate: EML Batch -5 & Concrete on the Moon

Soft Matter

- One award to support: *Liquid Crystal Film Experiment* with Kasetsart University with Thailand.

Preparing for the Decadal Survey Recommendations

- BPS currently has two focus areas: Quantum Science and Thriving in Deep Space (TIDES)

- Decadal Survey will recommend highly transformative keystone capabilities and campaigns

- BPS, will need vigorous community (academics and commercial) involvement to build the research community in line with the Decadal Survey recommendations

Research Activities by Discipline

Biophysics

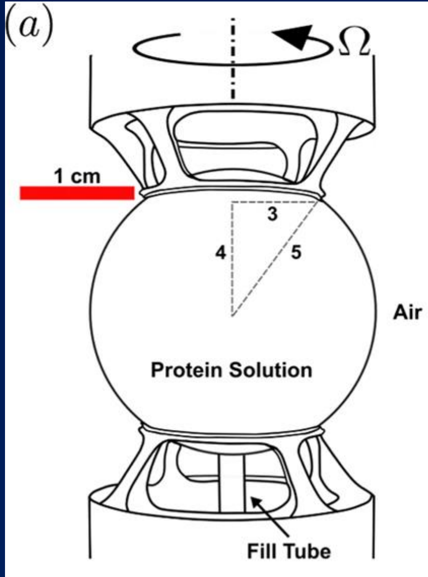
Biomaterials – RSD: Protein Fibrillization, Bioreactor - ISS

- Amyloid fibrils are misfolded proteins that self-assemble to form β-sheet rich fibrillar structures.
- Amyloid fibrils are relevant to amyloid diseases such as Alzheimer’s, Parkinson’s, prion diseases, and type 2 diabetes.
- Studying how these proteins clump together could help scientists understand the processes behind the development of these neurodegenerative diseases.
- Space provides an ideal environment to examine the formation of these protein clumps without the interference of containers.
- Ring Shear Drop focused on the effects of interfacial shear on the fibrillization kinetics of human insulin.
- Preliminary findings:
    - Increasing interfacial shear rate produced a monotonic increase in intrinsic fibrillization rate and a monotonic decrease in fibrillization time.
    - Protein concentration did not significantly impact the intrinsic fibrillization rate or times; however, a minimum fibril concentration for gelation was found.
    - Protein microstructure showed increasing aggregation and plaque/cluster formation with time.

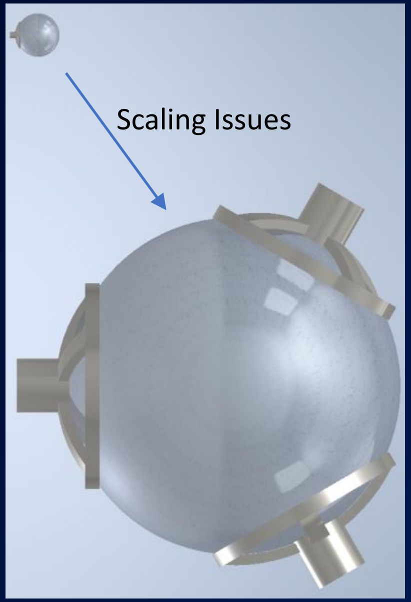
Image of fibrils taken from the bulk (Balaraj, Hirsa et al. Soft Matter 2017)

Dilute protein solution droplet in nearly containerless bioreactor on ISS.

Schematic of the ring shear drop apparatus



RSD

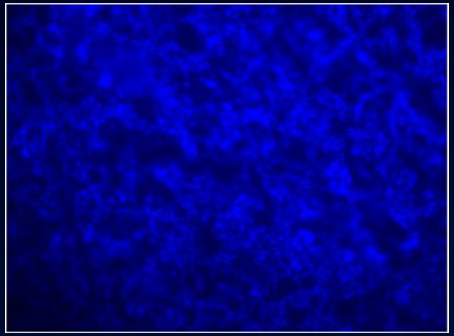


Future Opportunities – Biophysics

- Partner with Space Biology

Biofilms

- Biofilm growth has been observed in Soviet/Russian (Salyuts and Mir), American (Skylab), and International (ISS) Space Stations, sometimes jeopardizing key equipment like spacesuits, water recycling units, radiators, and navigation windows.
- Biofilm formation also increases the risk of human illnesses and therefore needs to be well understood to enable safe, long-duration, human space missions. Here, the design of a NASA-supported biofilm in space project is reported.
- The adhesion of bacteria to surfaces and therefore the initial biofilm formation is strongly governed by topographical surface features of about the bacterial scale.
- Experiments conducted aboard the ISS will provide unique insight into the mechanisms of attachment, growth and subsequent proliferation of biofilms in the absence of convection, critically important for continued presence in space- both on ISS and long duration missions.
    - To search for potential solutions, different materials and surface topologies will be used as the substrata for microbial growth.
    - A novel lubricant-impregnated surface will be assessed for potential Earth and spaceflight anti-biofilm applications.
- Studies on the effects of the space environment on bacterial or fungal biofilms will help with mitigation strategies of biodegradation or biocorrosion of materials and biofouling of fluid systems.
    - Advance fundamental knowledge for developing materials that are resistant to or inhibit biofilm formation and growth.
    - Reduce the dependency on chemical agents, which are potential health and ECLSS hazards in closed spacecraft environments.



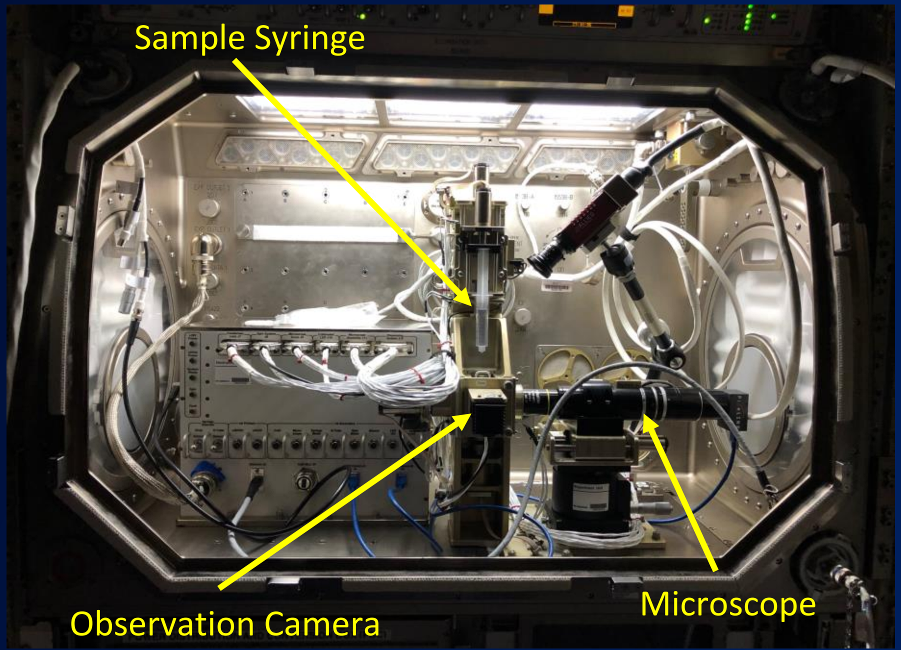
P. aeruginosa biofilm formed on quartz.

Biofilm sample tray

Extensive biofilm formation in ISS water recovery system

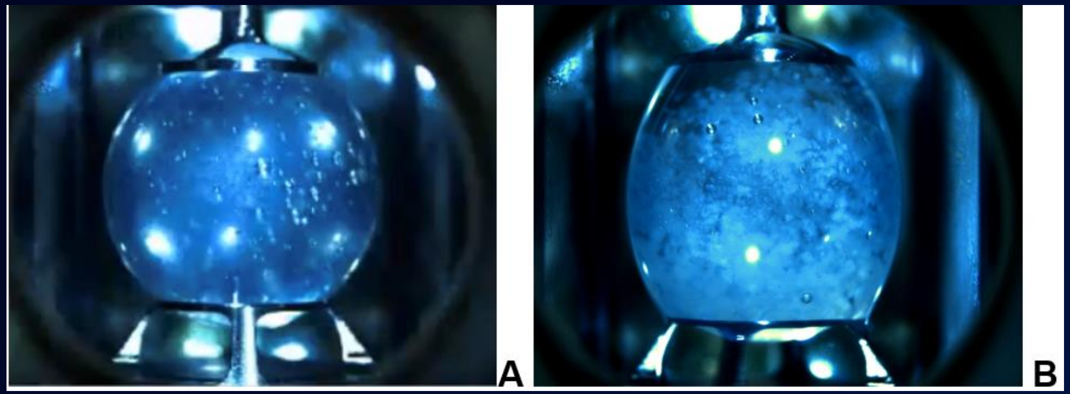
Containerless Bioreactor – from the RSD experiment

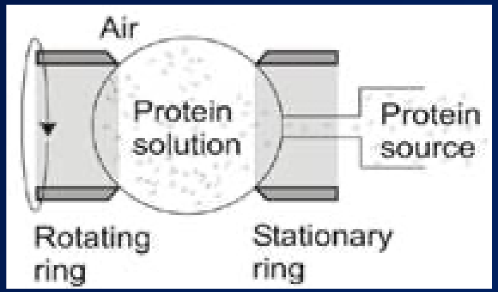
RSD was developed by BPS for the processing of biological fluids in microgravity. Using surface tension, RSD provides a containerless reactor in which the experimental fluid is held and processed in a spherical drop (corralled by surface tension). The drop is held between two small rings designed to minimize contact area. One of the rings is capable of rotation in order to induce flow inside the drop.



Launched on SpaceX CRS-18 – July 2019, Installed MSG, astronaut Nick Hague

Biological & Physical Sciences (BPS) - RSD was developed by BPS for the Amyloid Fibril Formation (AFF) experiment PI: Amir Hirsa/RPI,
ISS National Lab (ISSNL) is using the RSD hardware for biological experiments as well; the Interfacial Bioprocessing of Pharmaceuticals (IBP) experiment PI: Juan Lopez/ASU

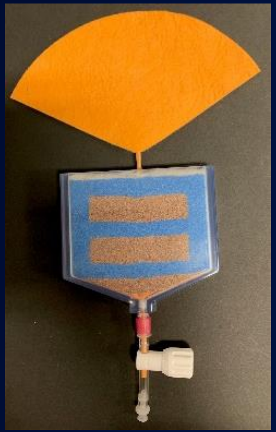




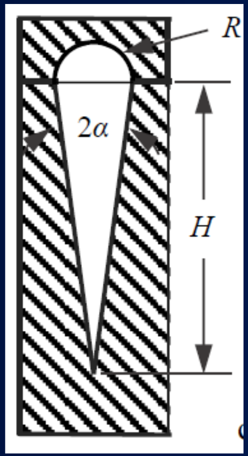
Plant Water Management –
using capillary driven flow strategies

Plant Water Management (PWM), PI: Mark Weislogel, Portland State University

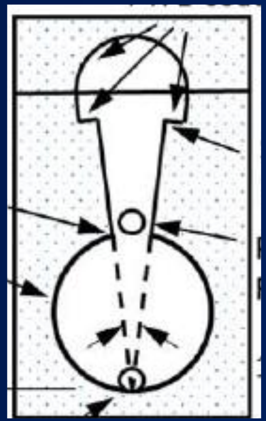
- Objective: Evaluate options for adequate hydration and aeration techniques for soil media and other farming strategies including but not limited to: Aeroponics, Hydroponics, and Soil-based media
- Soil (PWM-S): Establish a “capillary gradient” using material wettability to provide controlled to establish the ability to compare typical
- Hydroponics (PWM-H): Demonstrate the ability to utilize system geometry to provide positive water control for plant hydration.
- Root Accommodation Channel (PWM-HRAC): Provide accommodations for root growth as plant matures in a hydroponic channel.
- Parallel Channel (PWM-PHRAC): Examine system stability for growing multiple plants at different growth stages and water uptake rates.



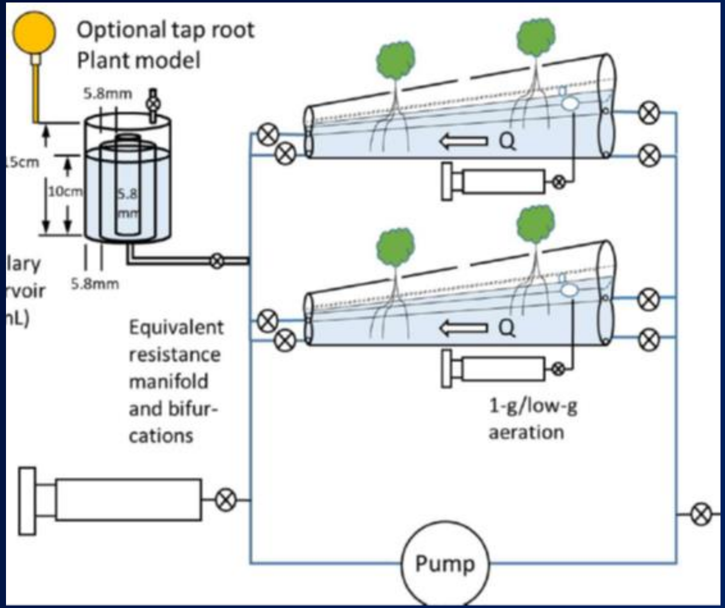
PWM –S test cell



PWM –H Cross-Section



PWM –HRAC Cross-Section



PWM –PHRAC Test Setup

Combustion

High Pressure Transcritical Combustion (HPTC)

Overview:

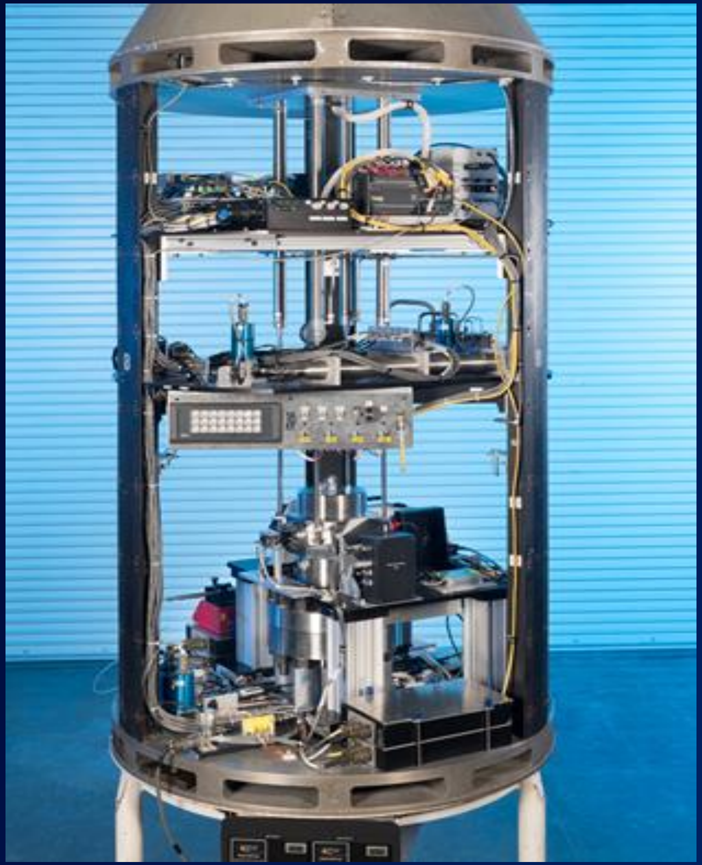
Transformative research to enable the design of future internal combustion engines moving to higher operating pressures to increase efficiency while simultaneously reducing pollutant emissions and novel applications such as supercritical water oxidation (SCWO) for waste incineration. Since the buoyant force scales with pressure squared, fundamental combustion studies in terrestrial laboratories are increasingly difficult because of the dominance of the buoyant force. The microgravity environment allows for extended length and/or time scales without the intrusion of a dominant buoyant flow. This in turn enables diagnostic techniques, that otherwise prove intractable in 1-g environments, to obtain transformative insights into supercritical phenomena.

Relevance/Impact:

Strong advocacy in military and industrial applications; e.g., advanced turbine combustors, advanced diesel engines, rocket engines (increased efficiency, power density and reduced emissions)

Fundamental thermophysical data and thermodynamic state data for supercritical fuel/oxidizer mixtures

Part of a larger GRC program in high pressure transcritical phenomena that has international collaborations (CNES) and interest from HEO (SCWO).



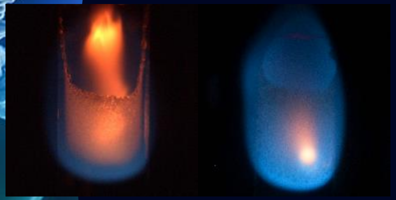
HPTC Drop Tower facility

Spacecraft Fire Safety - Solid Fuels

BPS Portfolio - Solid Fuel Ignition and Extinction (SoFIE)

Material Ignition and Suppression Test (MIST)
Fernandez-Pello: UC Berkeley
Fundamental experiments of solid material ignition from an external heat source

Spacecraft Materials Microgravity Research on Flammability (SMμRF)
Olson: NASA GRC
Flame spread experiments studying the flammability limits of solid fuels



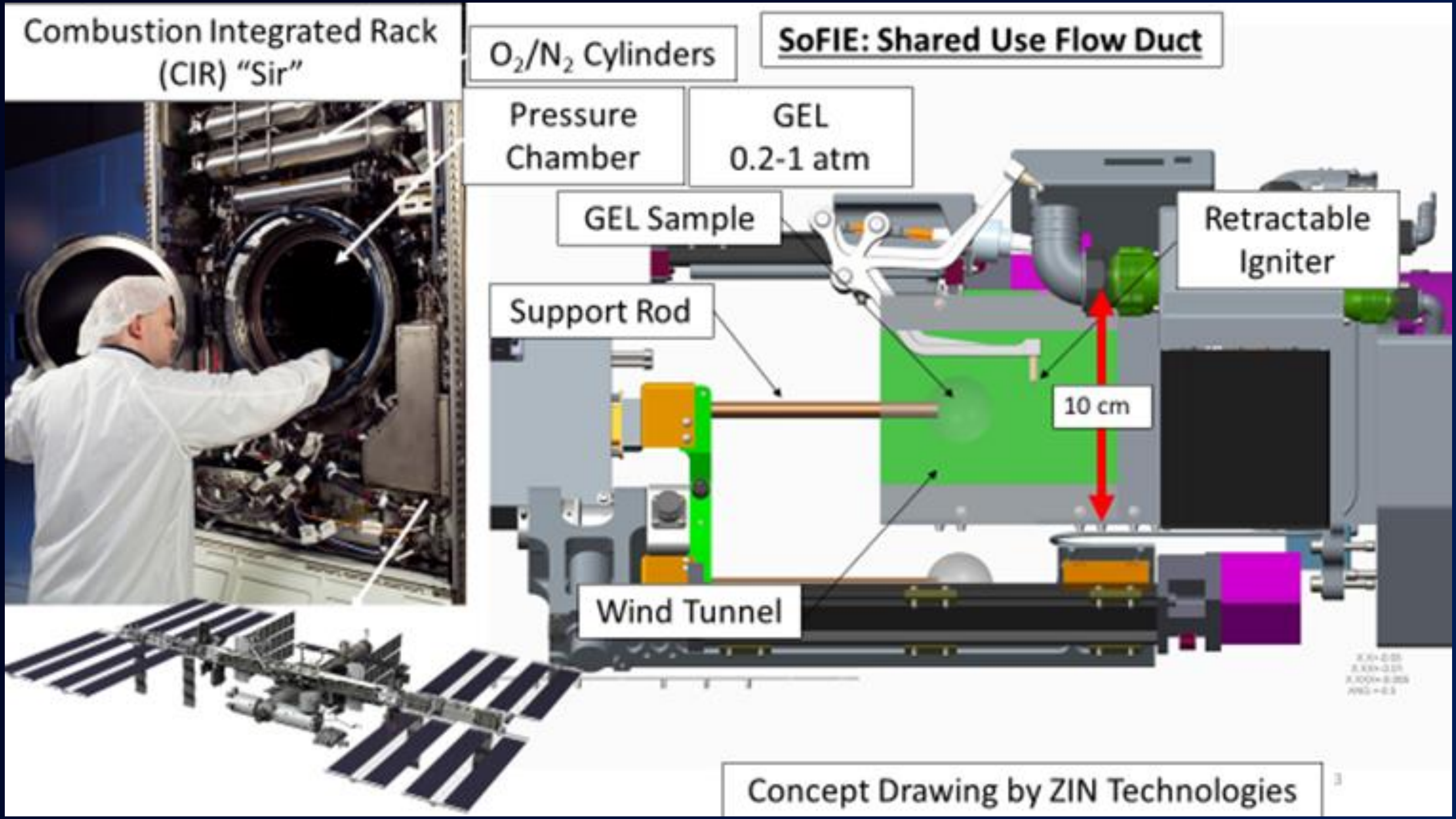
Narrow Channel Apparatus (NCA)
Miller: San Diego State University
Flame spread experiments focused on thick polymeric materials

Residence Time Driven Flame Spread (RTDFS)
Bhattacharjee: San Diego State University
Opposed-flow flame spread over thin acrylic sheets to examine fuel thickness effects

Growth and Extinction Limit (GEL)
T'ien: Case Western Reserve University
Investigating effect of gravity, flow, O_2, pressure, and fuel preheating on the combustion of polymeric spheres

Use of the Combustion Integrated Rack -

Flammability of Solid Fuels for Fire Safety



Flammability Limits At Reduced-g Experiment (FLARE)

JAXA PI: Prof. Osamu Fujita, Hokkaido Univ.
US Co-Is: Dr. Sandra Olson, NASA GRC
Dr. Harold Beeson, NASA
Prof. Carlos Fernandez-Pello, U. C. Berkeley
International Co-Is: Many Japanese Co-Is, Guillaume Legros, U. Pierre Marie Curie, Thomas Rohr, ESA, Marika Orlandi, ESA
Project Manager: Shigeki Kamigaichi, JAXA
Project Scientist: Masao Kikuchi, JAXA

Objective

To develop a methodology to correlate material flammability limits in normal gravity and microgravity, which allows quantitative estimation of material flammability limit in microgravity based on the flammability data obtained on the ground. The project involves an international team including JAXA, NASA, ESA and universities in Japan, USA and France.

Experimental Approach:

- Perform extensive research via ground-based experiments, including 1g and parabolic flight tests, and via theoretical formulations.
- Flight experiments on orbit in ISS/KIBO will be performed to verify the correlation.
- By the end of the project, a new fire safety standard test method for screening spacecraft materials will be proposed that addresses the shortcomings of existing standard test method such as NASA STD 6001B.

Relevance/Impact:

Fundamental Science – studying materials flammability in space allows us to accurately control the flow field and thus elucidate the importance of a critical Damkohler number (flow time /reaction time) on flame extinction. Efficiency - The anticipated improved methodology should reduce time and cost for the spacecraft material screening.
Safety - Terrestrial fire safety; spacecraft fire safety

Development Approach:

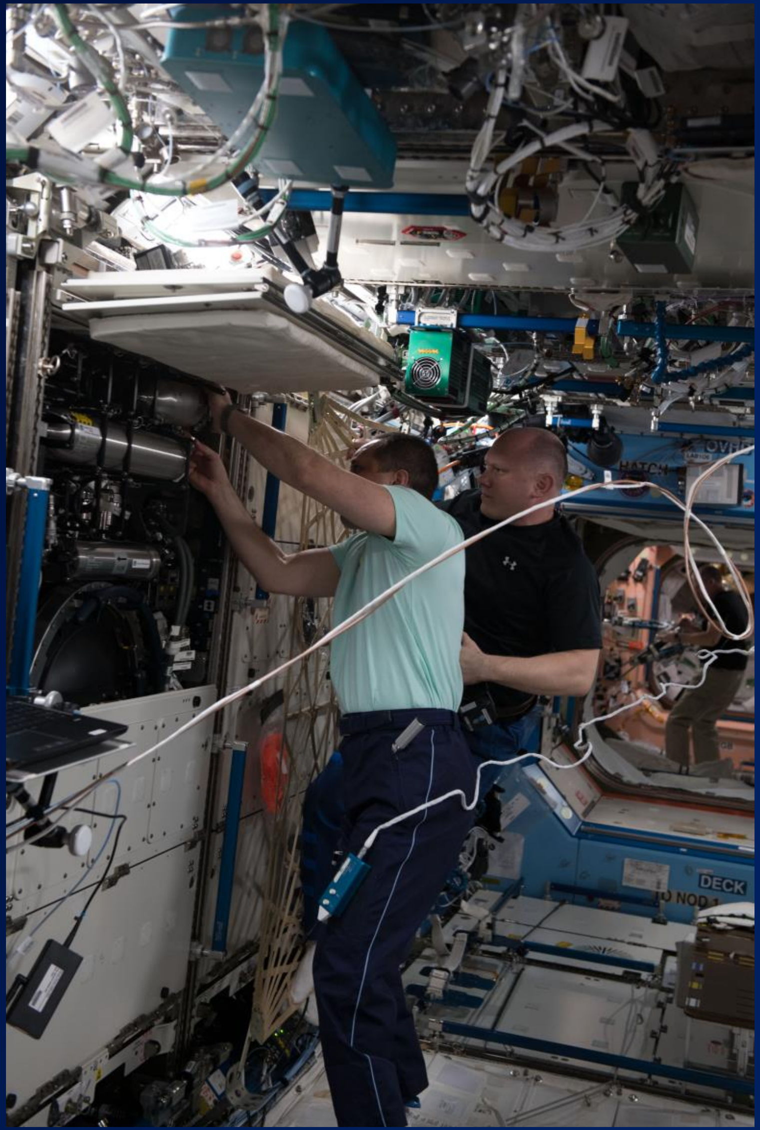
Experiment uses same hardware as JAXA’s “Solid Combustion” International research team

Combustion Research with Roscosmos

Investigations:

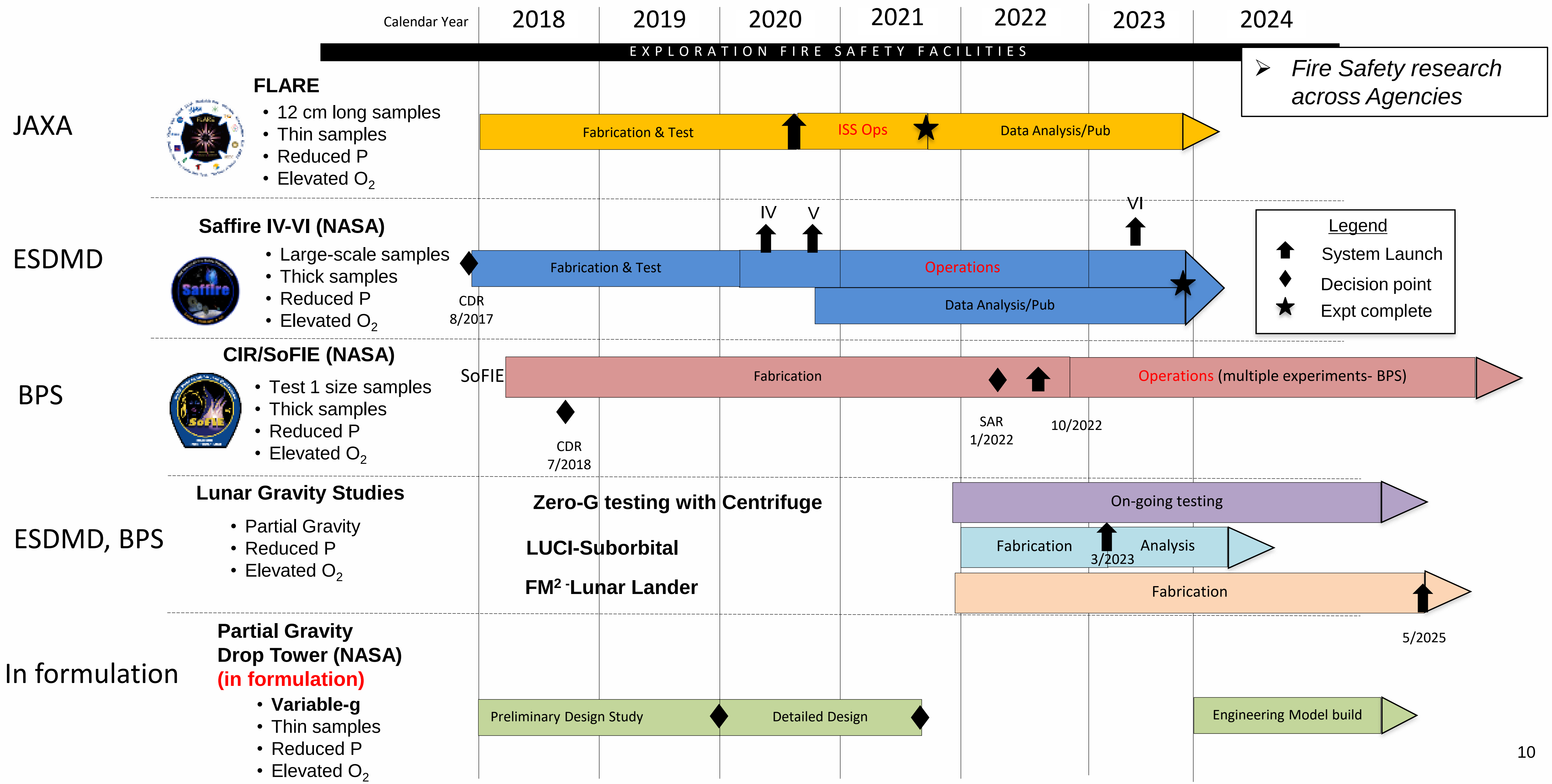
- SoFIE - Material Ignition and Suppression Test (MIST)
- SoFIE - Growth and Extinction Limit of Solid Fuels (GEL)

✓ ACME – Advanced Combustion via Microgravity Experiments - ISS ops completed



Cosomonauts Anton Shkaplerov (foreground) and Oleg Artemiev (background) performing a gaseous fuel bottle swap for the ACME experiment, “Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames)”

International Roadmap - Reduced Gravity Plan for Flammability Studies



Future Opportunities - Combustion

- Fundamental – Transcritical Combustion
  Gaseous Combustion
- Exploration - Fire Safety, Flammability of Solid Fuels

High Pressure Transcritical Combustion (HPTC)

Ground Based - Drop Tower

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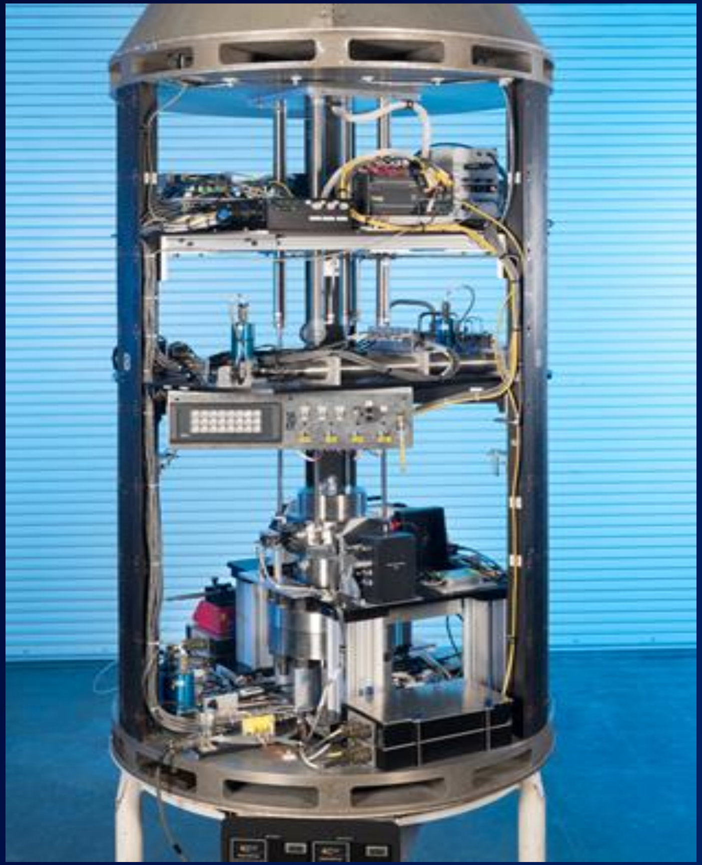
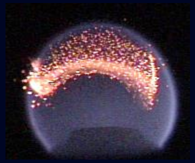


HPTC Drop Tower facility

Fundamental Combustion - Gaseous Fuels

Advanced Combustion via Microgravity Experiments (ACME)



Burning Rate Emulator (BRE) - Quintiere & Sunderland: UMd
A fire safety experiment using gaseous fuels to study solid fuel flammability

Electric-Field Effects on Laminar Diffusion Flames(E-FIELD Flames)
Dunn-Rankin: UCI
An experiment using electric fields to control flames

Flame Design - Axelbaum: WUStL et al.
Experiments examining soot inception and transport and flame structure

Structure and Response of Spherical Diffusion Flames (s-Flame)
Law: Princeton
An investigation studying soot formation/destruction mechanisms and combust
chemistry

Coflow Laminar Diffusion Flame (CLD Flame) - Smooke and Long: Yale
Detailed experiments on the structure and stability of gas-jet diffusion flames

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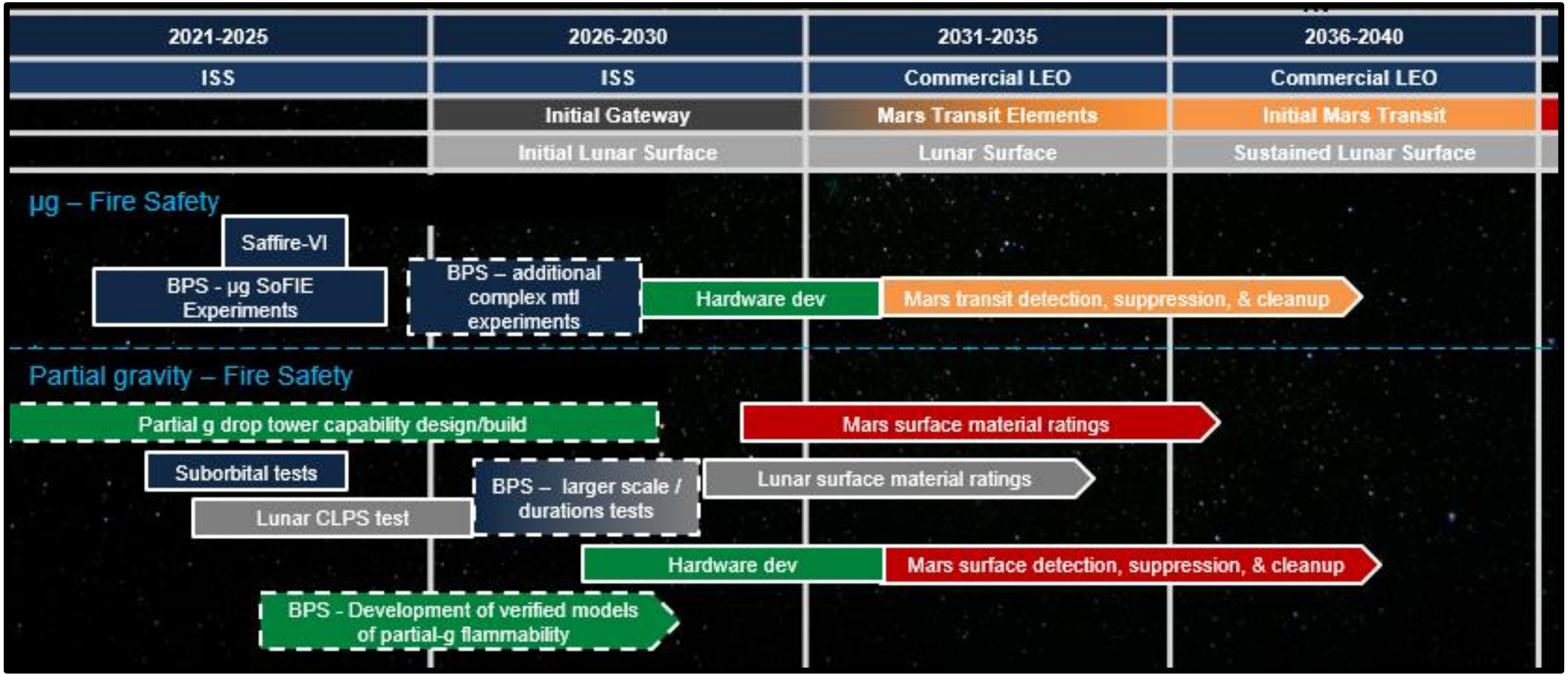
Notional Roadmap of Combustion & Fire Research Support for Exploration Fire Safety



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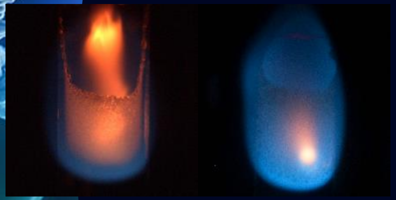

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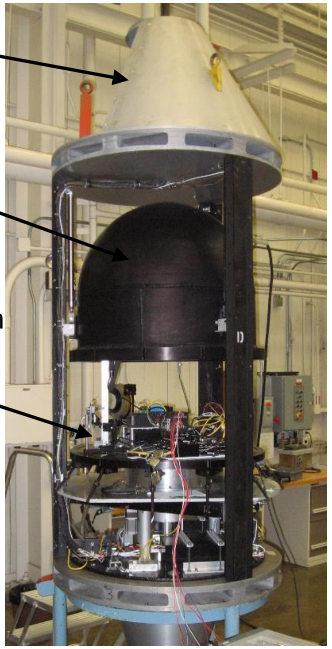
Progression of Partial-Gravity Test Methods

- Each test method builds on the methods below and to the left
- The New Shepard test method may become the "workhorse" for flammability testing if the proof-of-concept test is successful (early 2023)



ZGRF Centrifuge Rig (5 sec)

- Many tests
- Large Coriolis forces
- Short burn duration

Parabolic Aircraft (10 -20 sec)

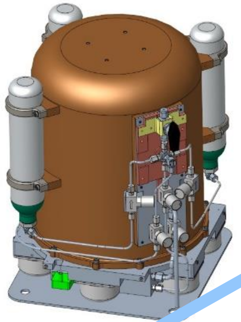
- Partner with ESA
- Short burn duration
- Few Opportunities
- G-jitter 0.01 to partial-g
- Currently to 21%O_2

Saffire partners from ESA in the reduced gravity aircraft

Blue Origin New Shepard Experiment (2 minutes)

- Lower Coriolis force (larger radius)
- Moderate burn duration
- Fewer opportunities (TBD)

Blue Origin, used with Permission (Erika Wagner)



CAD model of the Engineering Development Unit for the CLPS flammability experiment

Commercial Lander Payload Services (CLPS) on the Moon

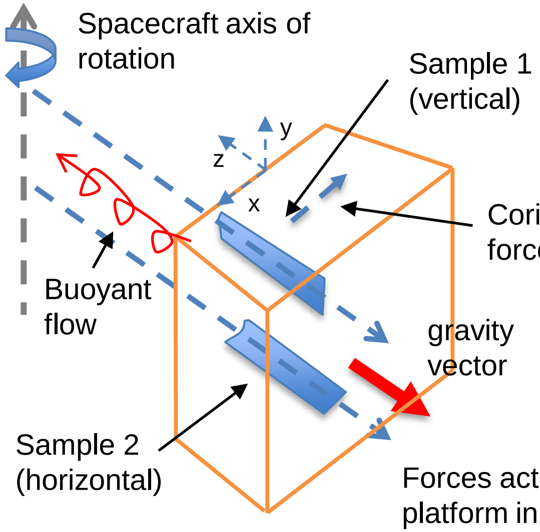
- Ground truth for Lunar-g flammability
- Small test samples
- Lunar Surface
- Very Limited opportunities

- A Lunar "ground truth" is necessary to validate results from the Earth-bound test platforms
  - Flammability limits and flame spread
- All test methods support numerical modeling

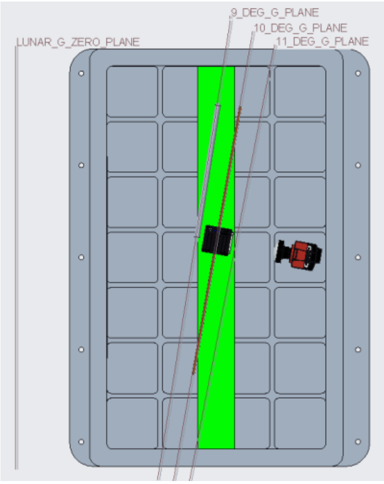
Lunar-g Combustion Investigation (LUCI) – Sub-Orbital

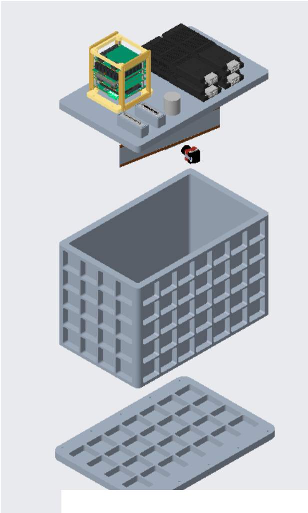
<u>Lunar Gravity Sub-Orbital Flight (Lunar-g Combustion Investigation - LUCI)</u>

- Objective: Investigate flame spread of SiBAL fabric and PMMA rod samples.
- Mission Concept Review - aligned the concept with Exploration Capabilities Office, HLS Materials and Process personnel
- Working with Blue Origin to develop and tailor test plans
- Flight is still planned for 1st Quarter of CY2023
- Will provide 2-minute partial-g test capability to extend drop tower testing



Forces acting on a rotating platform in 0-g.





Left: Concept for the experiment enclosure; Below: Double locker for the LUCI experiment in the experiment stack.

Above: Sample alignment and camera view inside the combustion chamber.
Below: Payload locker configuration in the Blue Origin New Shepard capsule.

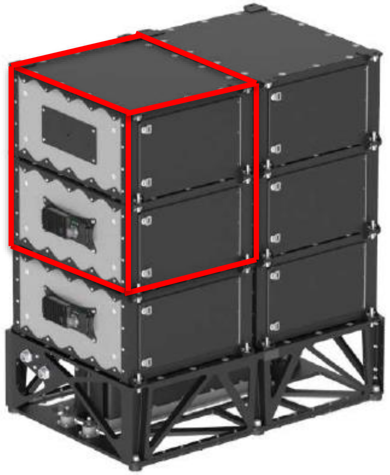
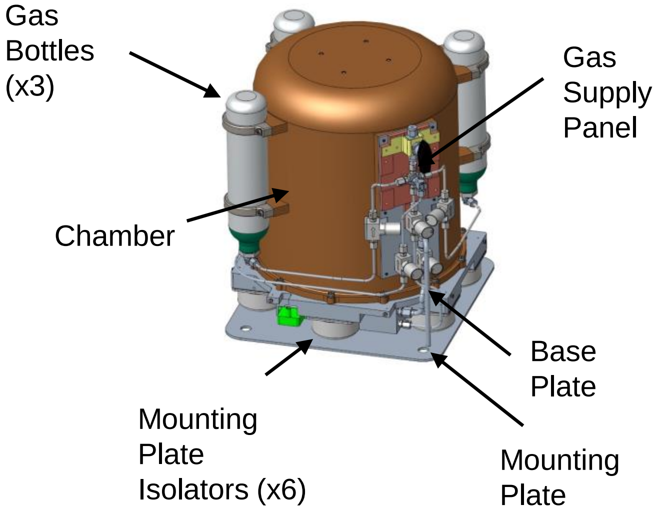


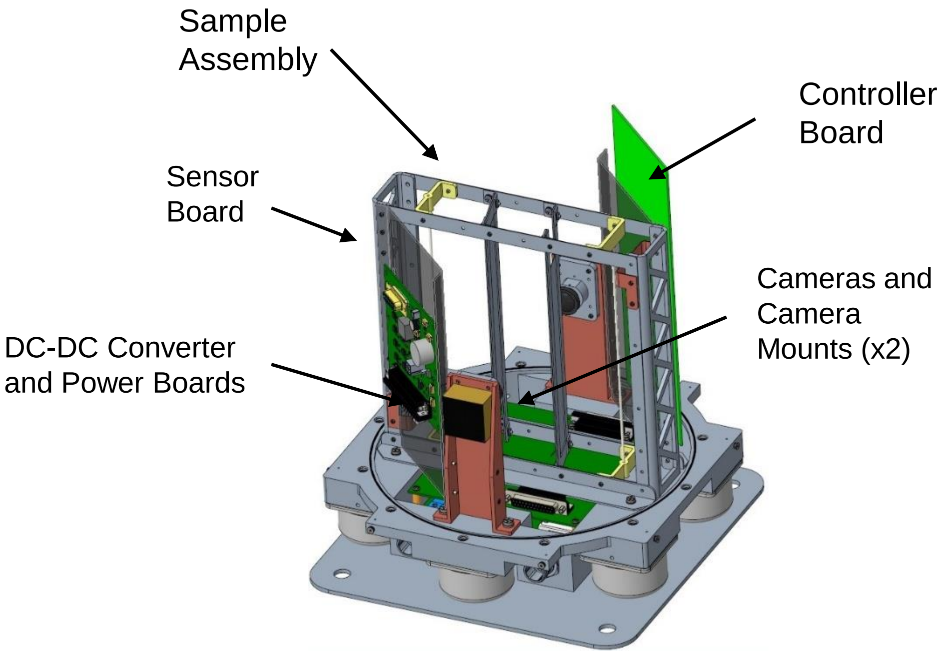
Figure 3-2
Payload Stack with six single lockers

Spacecraft Fire Safety, *Flammability of Materials on the Moon (FM^2)* – *Commercial Lunar Payload Services*

- Objective: provide extended-duration ground-truth testing for flame spread, growth, and extinguishment for 4 samples that include SiBAL fabric and PMMA rod samples.
- Working with Mars Campaign Development-Exploration Capabilities management and the HEOMD representatives to the CLPS Manifest Selection Board (CMSB) to get manifested on a CLPS mission
- CP-22 is scheduled to launch in February 2026
  - Destination is Lunar South Pole
  - Delayed from May 2025 launch
  - Flight Hardware Availability is now May 2025



CAD model of the external FM^2 design (Base plate is 28.5 cm x 28.5 cm; Chamber is 38.5 cm tall. Maximum weight is 25 kg)



CAD models of the internal FM^2 design

Fluid Physics

BPS Research: Advanced Thermal Management Technologies
applicable to THERMAL-472, THERMAL-483, THERMAL-519, THERMAL-604

Title: **Flow Boiling and Condensation Experiment - ISS**

PI: Prof. Issam Mudawar, Purdue University, Mojib Hasan, NASA GRC

Objective:

- Obtain flow boiling data to validate models for microgravity flow boiling critical heat flux (CHF) and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent CHF.
- Obtain condensation data to validate models for microgravity behavior.

Status: ISS Flow boiling tests successfully completed in July, 2022. Condensation tests to start in 2023.

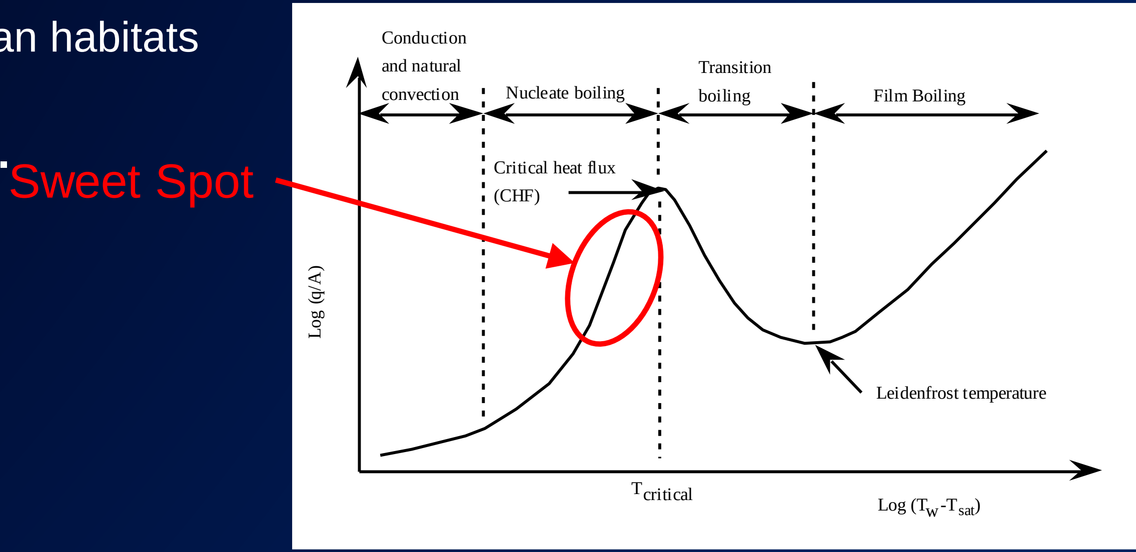
Applications:

- Thermal Control for ECLSS in crewed spacecraft and lunar & Martian habitats
- Thermal management for rovers and spacecraft
- Energy conversion, Rankine power cycle, for large power demands.

Potential Technology Impacts:

More efficient heat transfer:

- – Isothermal temperature control
- – Reduced mass
- – Wider Range of Heat loads.



Boiling Heat Transfer

Flow Boiling and Condensation Experiment (FBCE)
Flow Boiling - CHF Results for Double-sided Heating

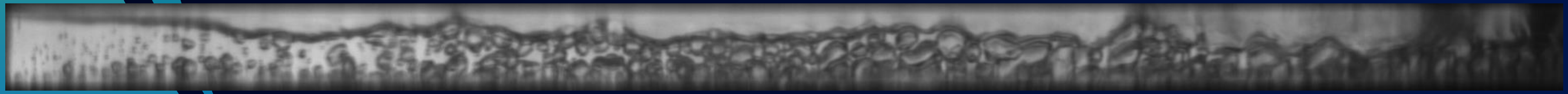
High Velocity Flow Rate
(1.9 – 2 m/s)

Horizontal 1g

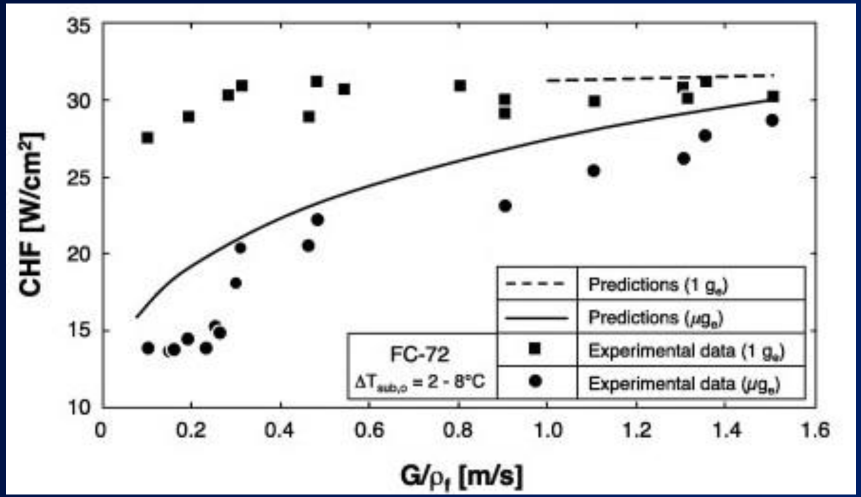
μg

Low Velocity Flow Rate
(0.1 - 0.11 m/s)

Horizontal 1g



μg



Critical Heat Flux as a Flow Rate

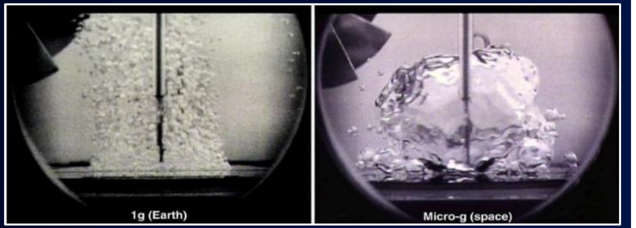
The Key to Fast Charging Electric Cars Is Flying 248 Miles Above Our Heads.
Popular Mechanics, Nov. 11, 2022

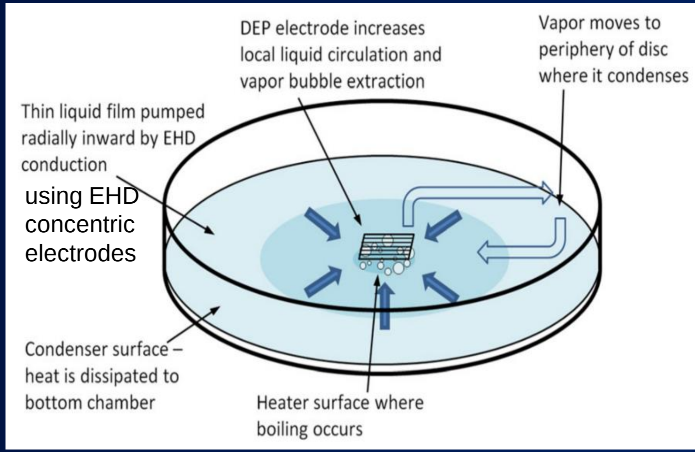
FBCE Breakthrough Application to Electric Vehicle Charging

- *What is unique about our new technology is ability to charge EVs in less than 5 minutes, eliminating a major obstacle facing the EV market!*
- *And what is important to NASA is that this technology utilizes science learned from our NASA research, namely using subcooled flow boiling of dielectric fluid to greatly enhance cooling of the conductor within the charging cable, which allows delivery of unprecedented 2,400 Amps, compared to 520 Amps for todays most advanced chargers on the market.*
- *The new technology is subject of a joint patent (pending at present) between Purdue University and Ford Motor Company.*

Advanced tech designed to cool NASA spacecraft could find its way into next-gen EV charging stations.

BPS Research: Advanced Thermal Management Tech.
applicable to THERMAL-604





EHD experiment concept

Title: **Electrohydrodynamic (EHD) Expt.**

PI: Prof. Jamal Yagoobi, Worcester Polytechnic Inst.

Jeff Didion, NASA GSFC

Objective: Develop theoretical foundation and test the effects of microgravity on electrically generated two-phase flow and an electrically driven liquid film boiling using a dielectric fluid.

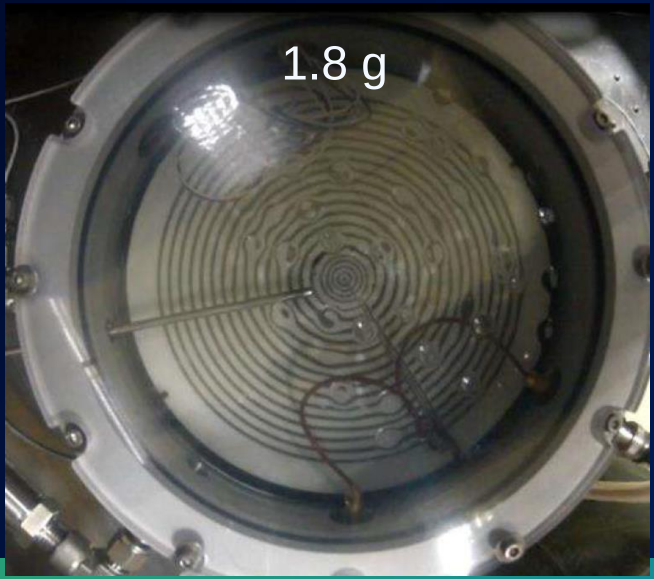
Application: Electric field based, two-phase thermal management systems

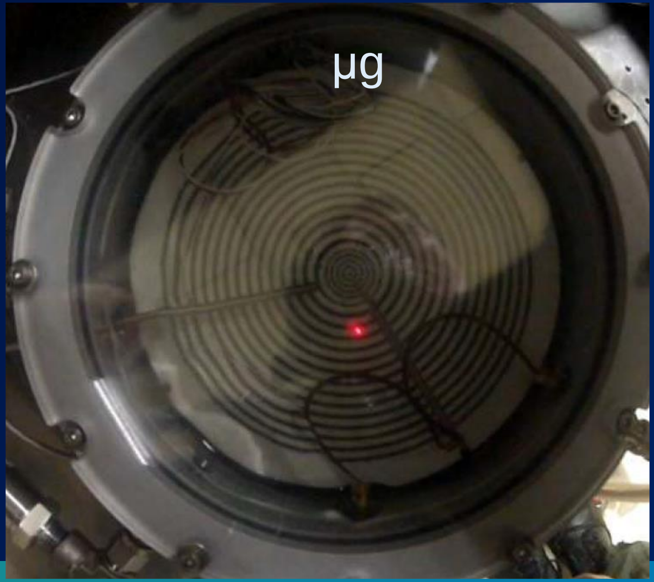
Benefits:

- Simple design, Light weight
- Non-mechanical, no rotating machinery
- Low power consumption
- Low acoustic noise

Potential Technology Impacts:

- Cool high powered electronic chips
- Smallsat Thermal Management





Title: ZBOT-NC Experiment (Non-Condensable Gas Effects) - ISS

PI: Dr. Mohammad Kassemi (Case Western Reserve University)

STMD Application: CFM-462, CFM-477. CFM-492, CFM-1194

Objective: Investigate the impact of Non-Condensable Gas (NCG) pressurants on tank pressure control in microgravity

Key science questions to be investigated & knowledge gained:

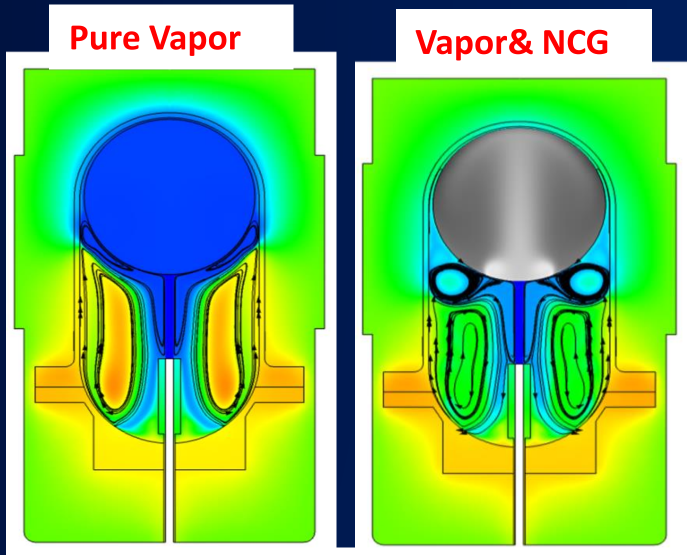
1. Can NCGs build a transport barrier in the ullage and disrupt tank pressure control in microgravity?
2. What are the kinetic effects of NCGS on interfacial condensation and tank depressurization?
3. Can a unique Marangoni convection generated by NCGs divert the subcooled jet away from the liquid/vapor interface and change the flow structures in the tank?

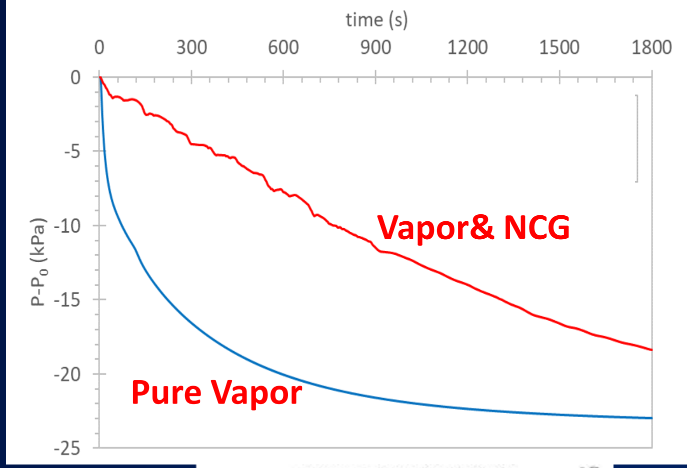
Anticipated Technology Impact:

- State-of-the-Art CFD model developed and validated for NCG effects to aid the propellant tank scaleup design
- Determine whether the current axial jet mixing pressure control strategy is effective in presence of NCGs in microgravity
- Shift to autogenous pressurization or use droplet injection cooling

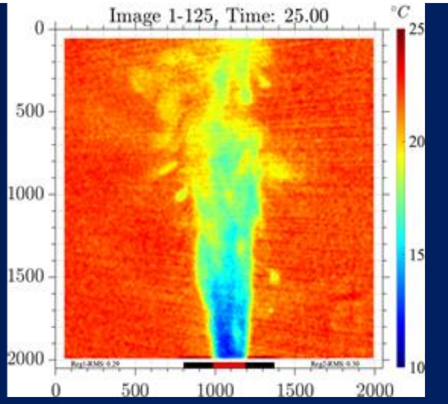
CFD model predictions of change in flow structure and pressure drop rate due to NCG effects during jet mixing in microgravity

Need Microgravity data to validate these crucial predictions





Whole Field Quantum Dot Thermometry Diagnostics developed by ZBOT to capture signatures of Marangoni convection



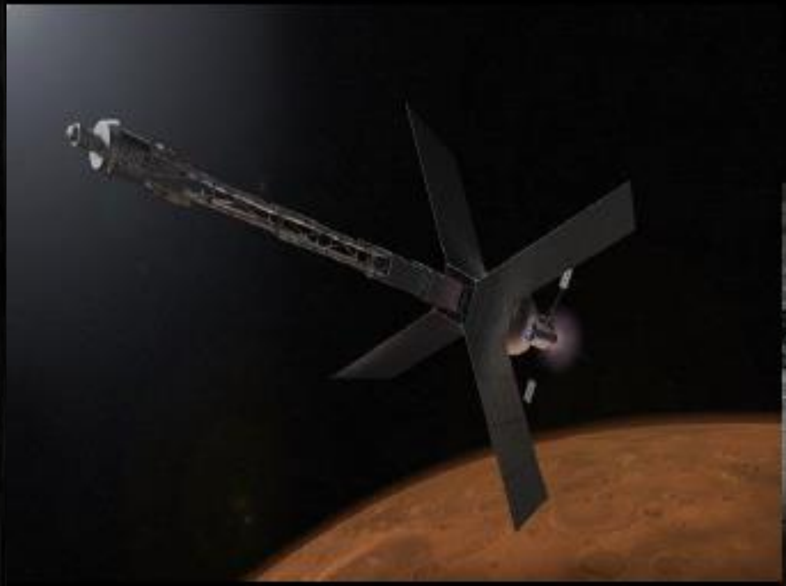
Future Opportunities – Fluid Physics

Exploration: Thermal Management/Control
Water Recovery and Purification
Cryogenic Fluid Management

Advanced Thermal Management Technologies to Enable Lunar and Martian Missions

Thermal management technologies that enable surviving the extreme lunar and Mars environments

Thermal Control for In-Space Transportation Systems



"Develop nuclear technologies enabling fast in-space transits"

"Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications"

Thermal Control for Surface Environment Survival

"Technologies that enable surviving the extreme lunar and Mars environments"

Science Instrument Survival
Power Systems
Spacesuits
Habitats
Cold Tolerant Mechanisms
ISRU Commodity Production

Thermal Control for Entry, Descent, and Landing Systems

"Enable lunar/Mars global access with 20t payloads to support human missions"

"Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies"

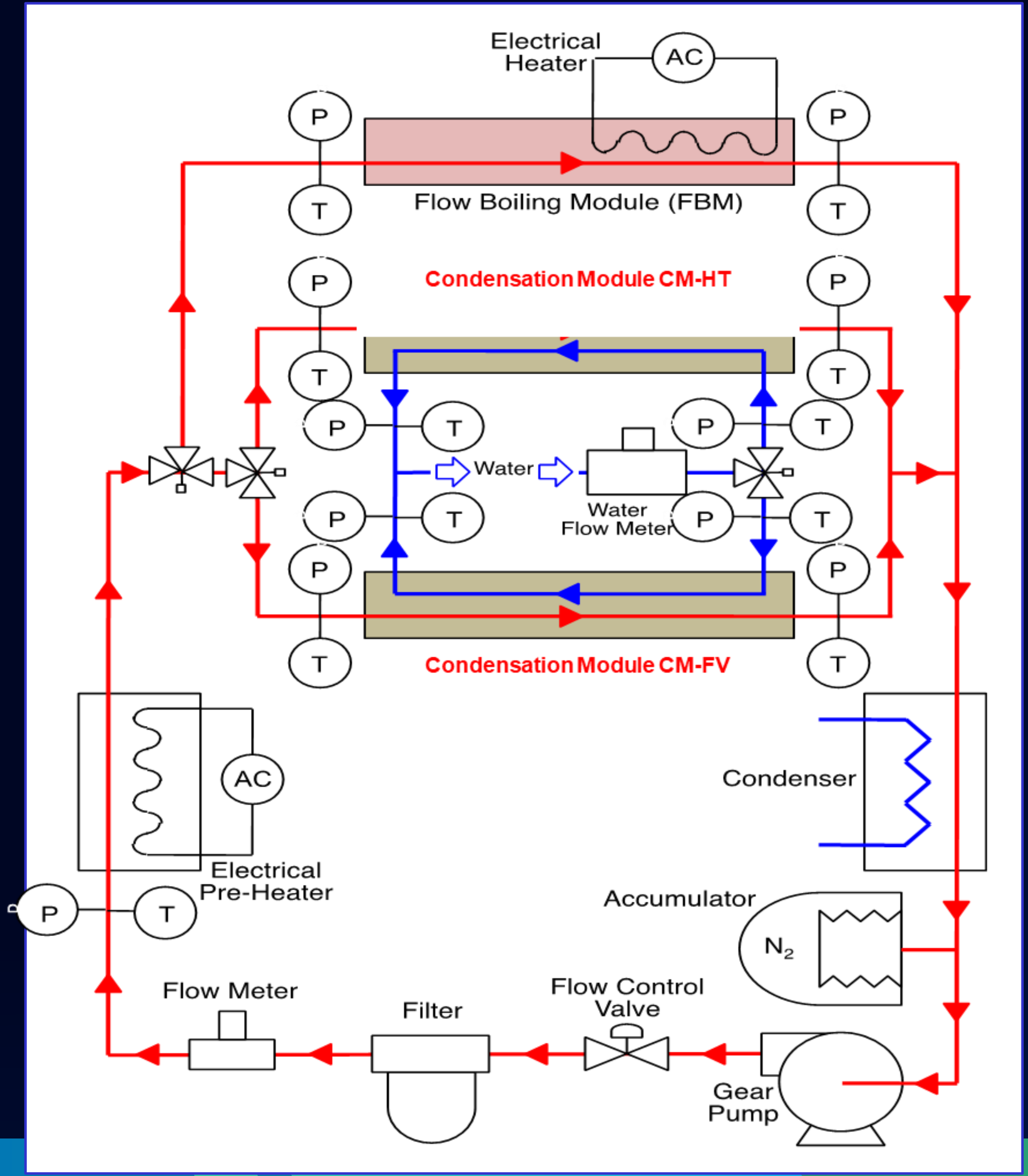
Topics of shared interest

High Level NASA Gaps

Strategic Technology Architecture Roundtable (STAR) – FY 2023 Gaps

- **THERMAL-472:** Human Class Variable Heat Rejection
- **THERMAL-483:** Rover Class Variable Heat Rejection
- **THERMAL-519:** Advanced Heat Pipes
- **THERMAL-604:** Advanced Cooling for Electronics

Flow Boiling and Condensation Experiment - ISS



Contains three test modules:

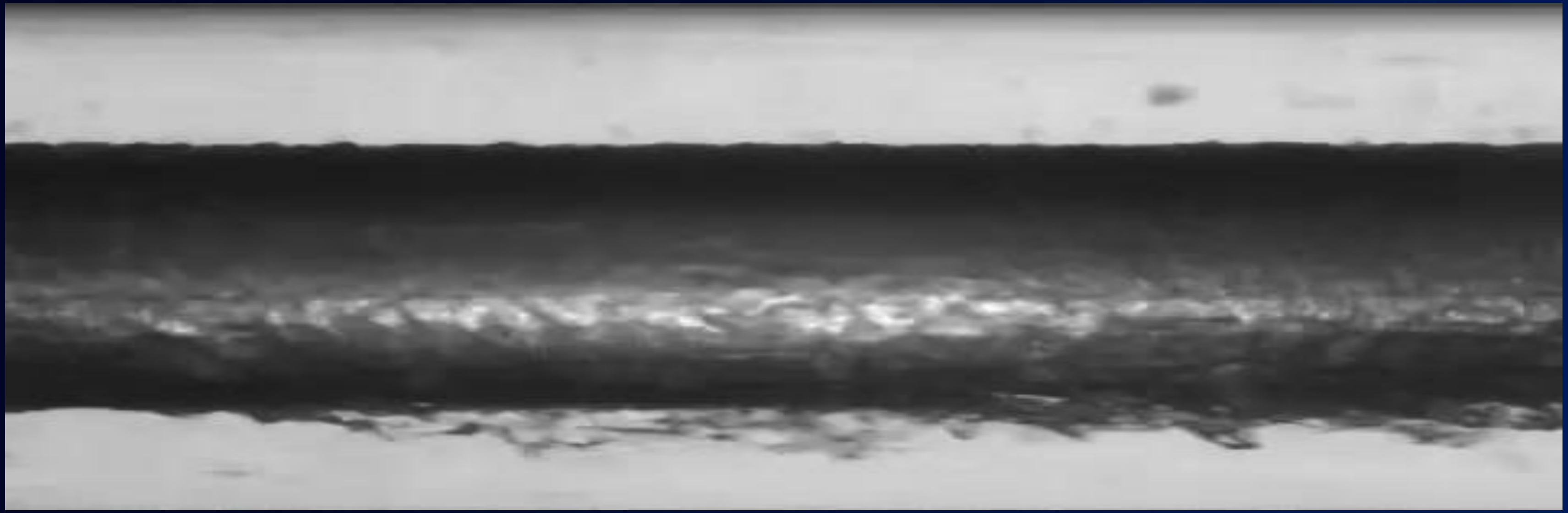
- ✓ Flow Boiling Module (FBM)
- ✓ Condensation Module CM-HT for heat transfer measurements
- Condensation Module CM-FV for flow visualization (Paused)

Sub-loops

- nPFH sub-loop
- Water sub-loop

Condensation in 1-g and reduced gravity (aircraft)

Horizontal 1-g



Reduced gravity

BPS Research: Advanced Thermal Management Technologies – Ground based
applicable to THERMAL-519 - STMD

Title: Pulsating/Oscillating Heat Pipes

PI teams: GSFC, JPL (numerical modeling) and Univ. Iowa grant, STMD grants.

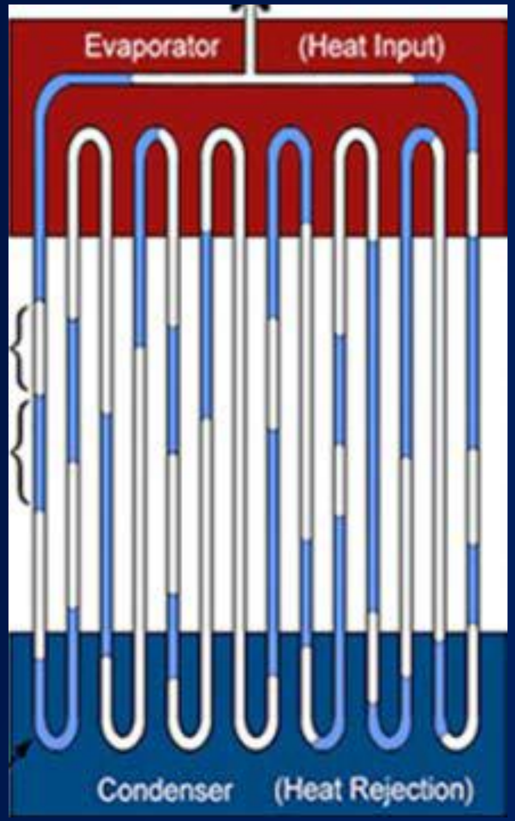
Objective: Explore Operational Envelope with extensive testing to validate models that focus on heat transfer and internal fluid dynamics to predict effective thermal conductance.

Research Focus

- Liquid film dynamics and heat transfer.
- Impact of fill level on contribution of latent vs. sensible heat transfer.
- Boiling nucleation in a fixed volume system.

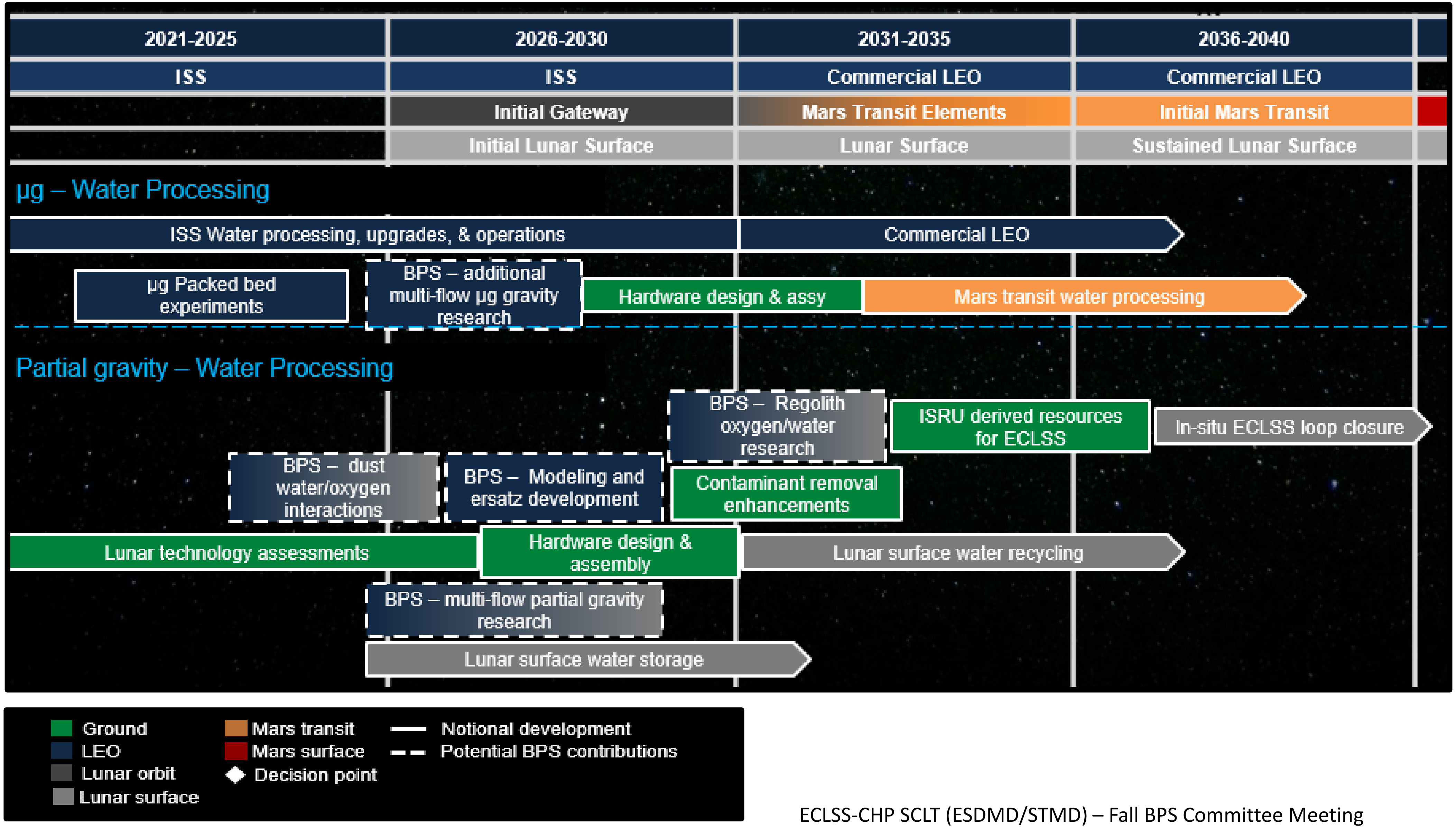
Potential Technology Impacts:

- Isothermal control for electronic cooling in satellites
- Cooling large space telescopes
- Extended heat transfer length. Smaller Radiators. Not prone to fouling.
- Lower fabrication costs.



Pulsating/Oscillating heat pipe schematic

Notional Roadmap of Multiphase Flow, Dust, and ISRU Resources Research Support for Exploration Water Processing



Packed Bed Reactor Experiment – ISS or CLD

- *Anomalies on the ISS Water Recovery System (WRS) indicate the pressure drop across restrictions is higher in m-G than 1-G. Also, unexpected accumulation of gas has occurred on the WRS filters during ISS operations.*

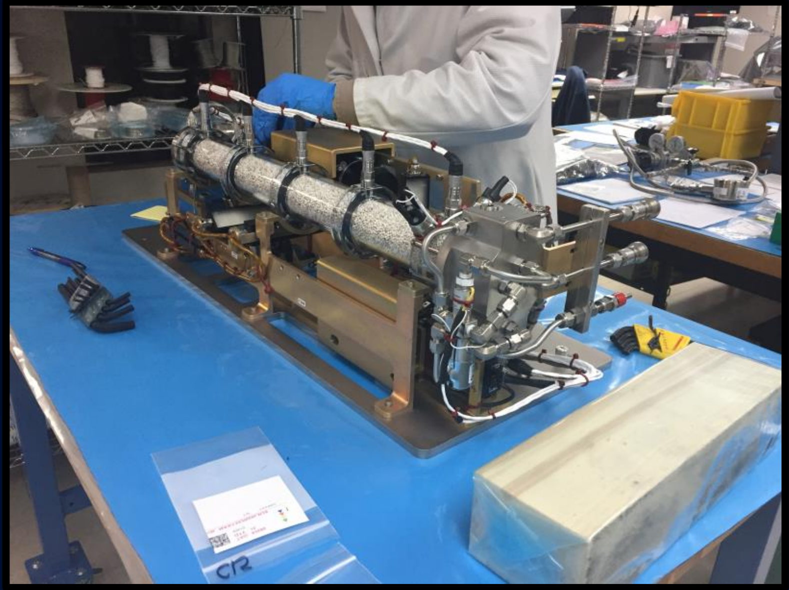
PBRE-2 test column with 2mm glass beads

BPS response –
PBRE- 1 & 2, PI: Brian Motil, NASA GRC
Co-I: Vemuri Balakataioh, University of Houston
Fundamental understanding of two-phase flow through wetting and non-wetting spherical beds to improve fundamental understating of packed bed reactors in reduced gravity and improve predictive numerical modeling.

PBRE-WR-1 and future series 2 -6, PI: Layne Carter, NASA MSFC

The hardware for packed bed reactor experiment (PBRE) examined the behavior of gas and water flows through a test section consisting of beads. PBRE-2 expands the parameter range of the previous set of tests to examine the effect of high gas flows through 2 mm glass beads. PBRE-Water Recovery is the first of a series of experiments in support of the Advanced Environmental Systems (AES) and will examine the flows through a catalyst particles used in the water processing assembly (WPA) aboard the ISS.

PBRE-Water Recovery test column with 3-mm alumina beads



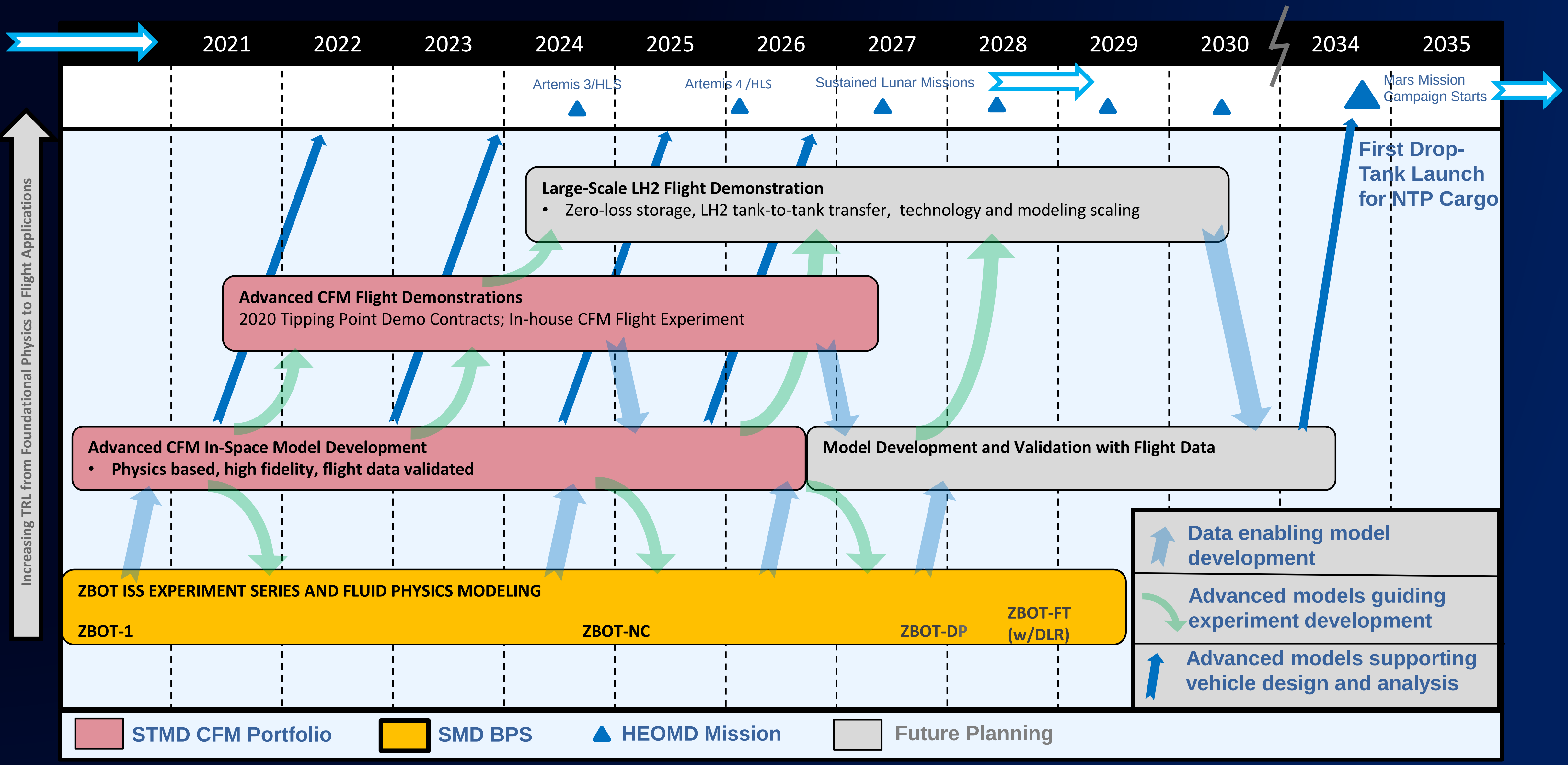
Next Steps: Utilize Tomography system with PBRE hardware to yield 3-D imaging of voids, gas bubbles and liquid - vapor interface

Packed Bed Reactor Experiment Water Recovery 1 - 6 (PBRE -WR): BPS – AES Collaboration

Experiment name/test sect	Tasks	SLPSRA costs	AES costs	Test section
PBRE-2 (SLPSRA) (SpX 16)	Camera repair, test material, Preflight testing, MI&O, hardware prep	PI and Co-I, PS, Grant, Cradle/test section	N/A	
PBRE-WR-1, Applied packing material (SpX 16)	Preflight testing, MI&O, hardware prep	Cradle/test section, Co-I/PS	PI, ISS WR packing material	
PBRE-WR-4 Purge Filter	Preflight testing, hardware prep, MI&O (coordinated through SLPS)	Co-I/PS	PI, new cradle with replaceable test sections.	
PBRE-WR- 5 Lee Orifice #1 & #2 Check Valve	Preflight testing, hardware prep, MI&O (via SLPS)	Co-I/PS	PI, orifice and valves	
PBRE-WR-2 Brine filter	Preflight testing, hardware prep, MI&O (via SLPS)	Co-I/PS	PI, brine filter	
PBRE-WR-3	Preflight testing, hardware	Co-I/PS	PI, urine transfer	
PBRE- WR -6 Flow Restrictor	Preflight testing, hardware prep, MI&O (via SLPS)	Co-I/PS	PI- Flow Restrictor	

Direct application to ISS Water Recovery System and precursor for future ECLSS systems

STMD Path from Foundational Physics to Enabling CFM for Crewed Missions



Title: ZBOT-DP Expt. (Droplet Phase Change Effects) – ISS, CLD

PI: Dr. Mohammad Kassemi (Case Western Reserve University)

STMD Application: CFM-462, CFM-477. CFM-492, CFM-1194

Objective: Study the effect of droplet phase change and transport on tank pressure control and tank chilldown in 0g.

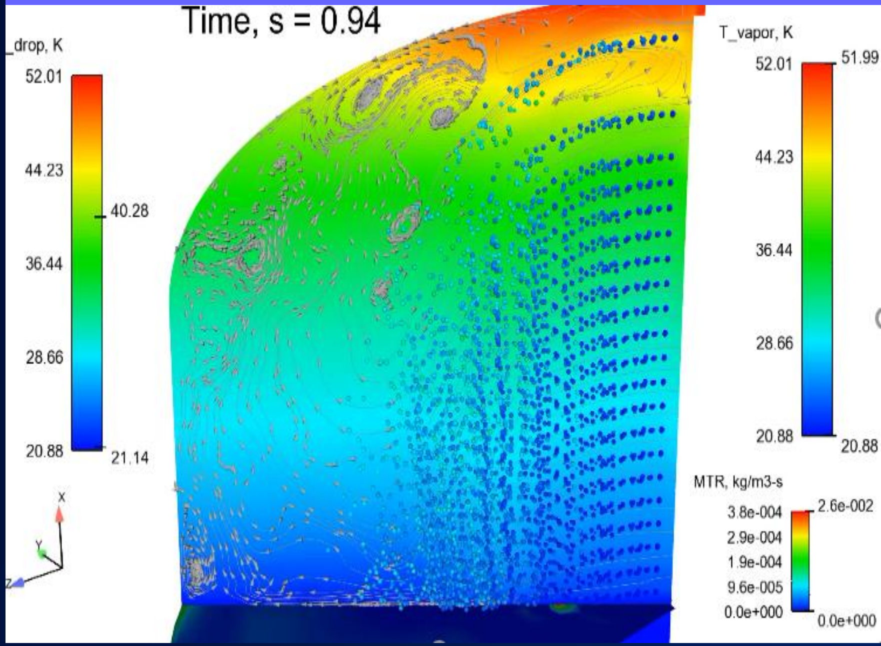
Key science questions to be investigated & knowledge gained:

1. How is transport of droplet in the ullage different in 0g?
2. What is the effect of droplet evaporation on tank pressure? Is it affected by non-condensable gases?
3. How is droplet-wall and droplet-interface heat transfer modified in 0g ?
4. What is the effect of flash vaporization at the walls?
5. Is the Leidenfrost effect strong enough to propel droplets away from the wall in 0g?

Anticipated Technology Impact:

- Droplet Injection cooling is gravity-dependent but never tested in microgravity – test data to show if this strategy is feasible for pressure control & tank chilldown in microgravity?
- State-of-the-Art CFD model developed and validated for droplet phase change/transport to aid the propellant tank scaleup designs

Droplet Injection Pressure Control in 1G

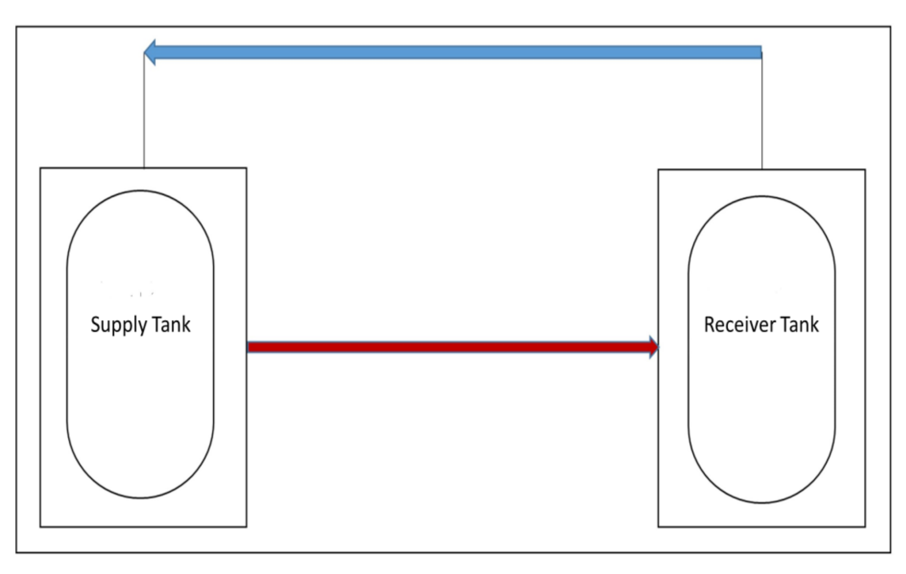


1G behavior of droplet injected using a spray bar during tank pressure control. How will these droplets behave in 0g?!

➔ Specific Questions 1-5

CFM – Tank to Tank Transfer Line, using the FBCE

- NASA plans to conduct boiling and condensation experiments aboard the ISS using the Flow Boiling and Condensation Experiment (FBCE), in the Fluids Integrated Rack. The FBCE is an integrated two-phase flow boiling and condensation facility intended to serve as a primary platform for obtaining two-phase flow and heat transfer data in microgravity using the research fluid, normal perfluorohexane.
- Once currently planned test runs for FBCE are completed, NASA intends to replace the original flow boiling module with a new boiling module that has a geometry that more resembles the propellant tank transfer process.
- Two selected teams are currently seeking to determine the best use of the new flow boiling module for the FBCE using simulant fluid, in support of in-space cryogenic propellant tank transfer research.
- Specifically, the new boiling module will investigate the flow boiling (film, nucleate, etc.) occurring in the transfer line using the research fluid, normal perfluorohexane. All proposal concepts must fit within FBCE hardware capabilities that are currently designed.



Simplified in-space cryogenic propellant refueling concept and experiment

ZBOT – FT: Zero Boiloff Tank - Filling & Transfer Experiment – ISS CLD

Investigator team:

DLR sponsored - Prof. Michael Dreyer – U. Bremen;
NASA sponsored - Dr. Mo Kassemi – CWRU

Objectives:

- Use a small-scale simulant fluid experiment and CFD model development to investigate and understand the effect of microgravity on evaporation, condensation and boiling phenomena and the associated two-phase flow transport regimes that **impact tank and line chill-down and tank to tank transfer operations** during refueling of spacecraft propellant tanks from orbiting fuel depots.
- Investigate the integrated system level dynamics of two-phase two-tank system in microgravity and assess if no-vent tank-to-tank transfer is feasible in microgravity for cryogenic refueling.

Collaboration Approach: Experiment concept driven by NASA STMD goals

- Ground based study – drop tower/aircraft testing DLR; numerical simulation NASA
- Flight hardware development – DLR
- ISS or Commercial LEO Destinations, launch, integration and ops – NASA ISS-PO and BPS

Application:

Cryogenic Fuel Depot, Lunar lander (Human Landing System)
In-Space Servicing, Assembly, and Manufacturing (ISAM), and Mars transit vehicles

- Propellant Tank Chill down and Propellant Tank Transfer Operations

Status:

- ✓ Ground Tests: 2019 – 2025, in progress
- ✓ DLR Phase A/0 flight experiment study – 1/2023 to 1/2024
- Flight experiment – contingent upon cost estimates from Phase A/0 study
- International Agreement for space experiment – first draft has been developed
- Flight hardware development **plan**: 2024 – 2028, ISS ops: 2028-29

NASA concept for an in-space propellant depot.

Materials Science

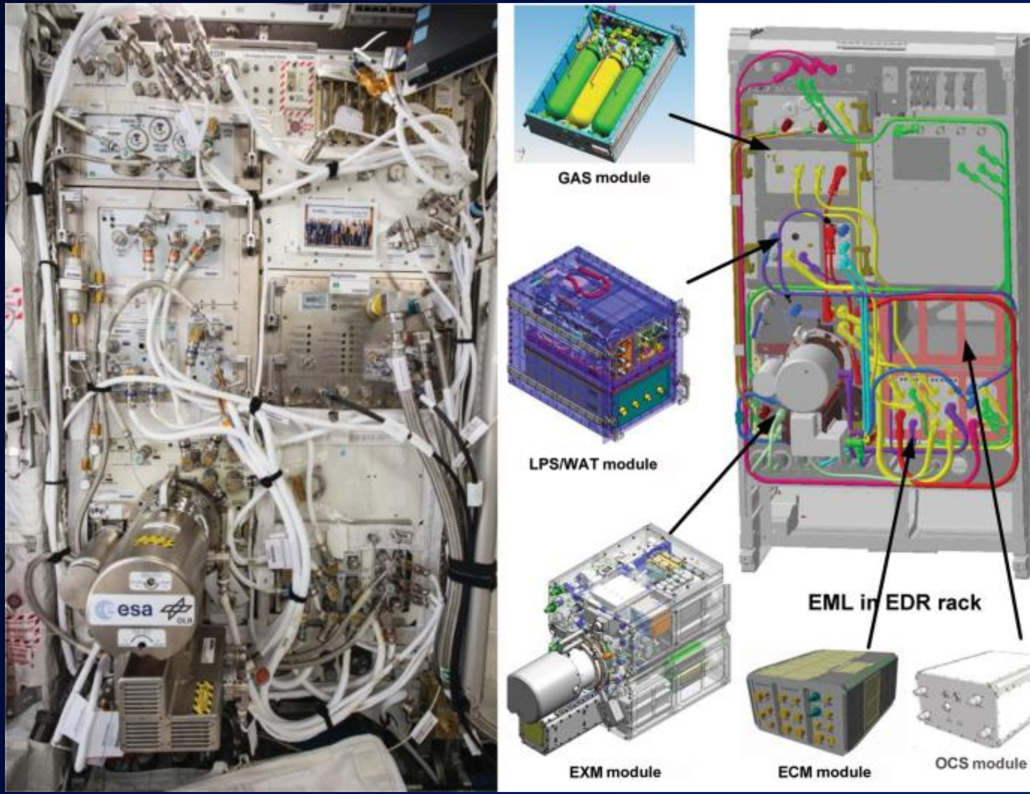
Electromagnetic Levitator - EML

Research Areas of Interest

Thermophysical properties of metal alloys. For both fundamental and applied (in-space manufacturing) studies.

International Space Station Electromagnetic Levitator (ISS-EML)

- A multi-user facility for the melting and solidification of conductive metals, alloys, or semiconductors in ultra-high vacuum, or in high-purity gaseous atmospheres.
- The heating and positioning of the sample are accomplished using electromagnetic fields generated by a coil system.
- Installed - European space laboratory, Columbus.

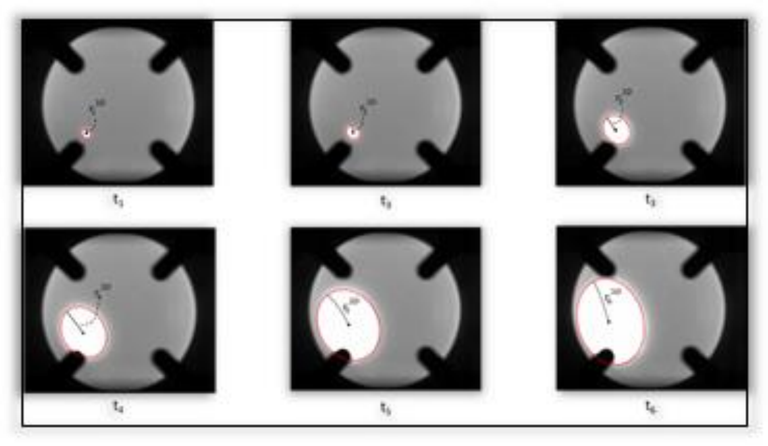


EML on board the ISS

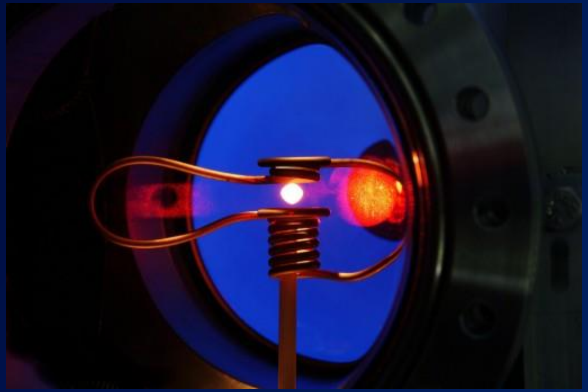
Thermophysical Properties - EML Batches 1-4

International Space Station Electromagnetic Levitator (ISS-EML) - ESA

- A multi-user facility for the melting and solidification of conductive metals, alloys, or semiconductors in ultra-high vacuum, or in high-purity gaseous atmospheres.
- The heating and positioning of the sample are accomplished using electromagnetic fields generated by a coil system.
- Installed in the European space laboratory Columbus.
- There are currently 3 US PIs with experiments on the ISS-EML
- Robert Hyers, University of Massachusetts
    - Objective: Investigate the thermophysical properties of high-temperature materials used for modeling of material production processes, e.g. additive manufacturing, welding, and casting.
- Kenneth Kelton, Washington University in St. Louise
    - Objective: Correlate the nucleation kinetics with the local structure of a liquid alloy by measuring its thermophysical properties. Applications include bulk metallic glass materials.
- Douglas Matson, Tufts University
    - Objective: Investigate the effect of fluid flow on the solidification path of aerospace alloys, and to measure the thermophysical properties of high-temperature materials. Applications include turbine blades, industrial welding, automobile components.



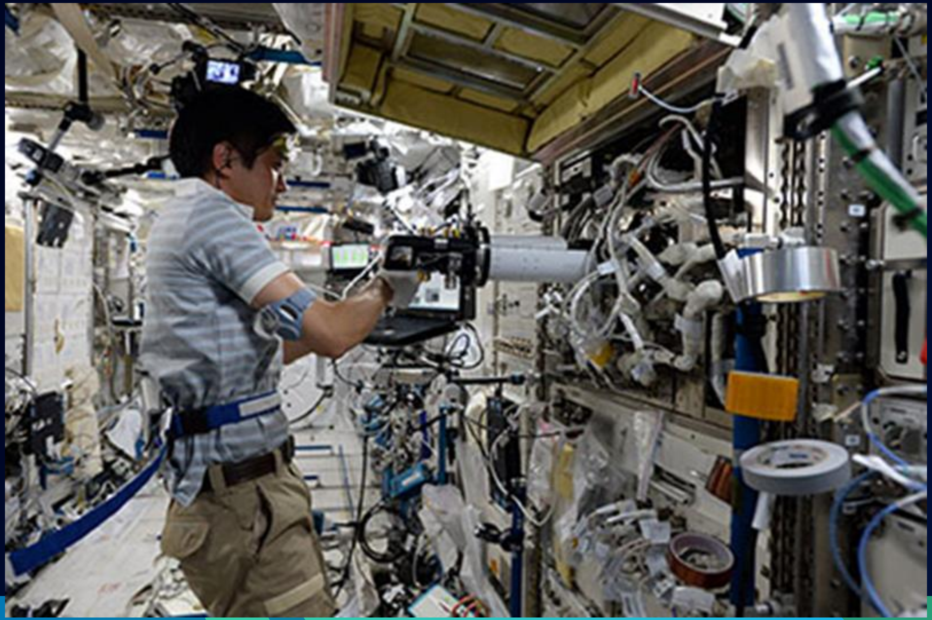
Growth velocity analysis of a ZrNi ISS-EML sample. Liquid is gray, solid is white.



Sample levitated in an EML at DLR.

Thermophysical Properties

Sample levitated in ELF on ISS during Dr. Matson's ops.



Electrostatic Levitator Furnace (ELF) on ISS

JAXA Electrostatic Levitation Furnace (ELF 1 -6)

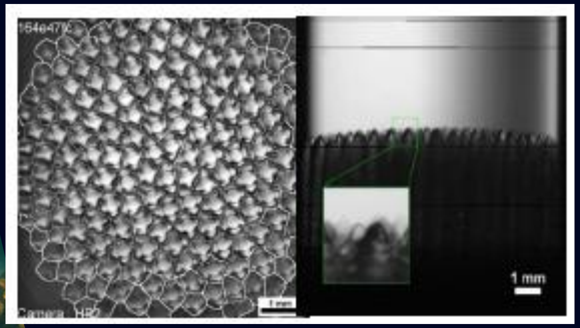
- Materials science facility for thermophysical properties (e.g. density, surface tension, a viscosity) measurement of molten metals, alloys, glasses, and oxides.
- ELF is installed in the MSPR-2 (Multi-purpose Small Payload Rack #2) in Japanese Experimental Module "KIBO" in the ISS.
- Samples are levitated with an electrostatic field and heated with 4 970nm 40W lasers.

US investigators:

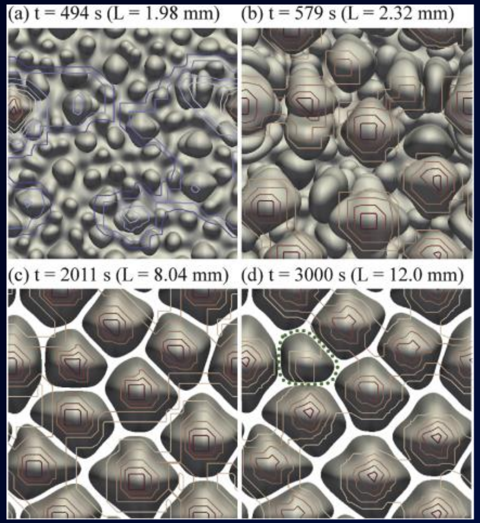
- Robert Hyers, University of Massachusetts
  - Objective: Advance the understanding of photo-refractivity, which has applications in holographic storage, adaptive optics, and phase-conjugate mirrors, using $Bi_{12}SiO_{20}$ and $Bi_{12}GeO_{20}$.
- Douglas Matson, Tufts University
  - Objective: Understand and control the sources of measurement error and to provide a baseline dataset for quantifying uncertainty in measurements (both space- and ground-based).
- Ranga Narayanan, University of Florida
  - Objective: Investigate a novel method to determine the interfacial tension, which i a property that impacts industrial processes such as semiconductor crystal growth and additive manufacturing.
- Richard Weber, Materials Development, Inc
  - Objective: Develop new understanding of the behavior of oxide liquid, glass and ceramic materials in extreme conditions and non-equilibrium conditions. Applications include photonics, lasers, and piezo electrics.

Solidification – DECLIC

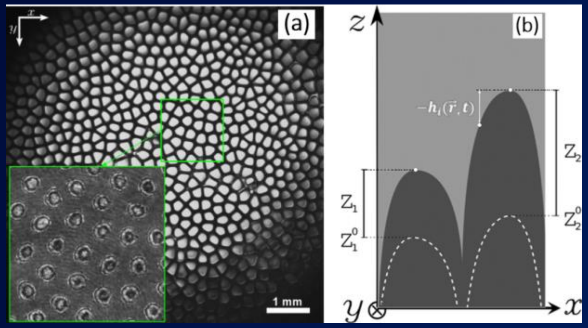
- **Device for the study of Critical Liquids and Crystallization – Directional Solidification Insert (DECLIC-DSI) is a facility that can be used to study directional solidification of transparent alloys, such as succinonitrile (SCN).**
- **These alloys solidify the same way metals do and form the same microstructures in the process.**
- **Dr. Rohit Trivedi, Iowa State University**
  - Objective: Examine the origin and growth of dendrite side-branches during directional solidification. Improved understanding of microstructure formation provides insight into enabling the development of advanced materials of commercial importance.



Axial and transverse views of dendritic interface in DECLIC-DSIR on ISS.
Mota, Ji, Lyons, Strutzenberg, Trivedi, Karma & Bergeon, IAC-19-A2.6.2 (October 2019).



Phase field model of interface shape and thermal field for v=4 µs in DECLIC-DSI composition.
Song, et. Al., Acta Mat, 150 (2018)

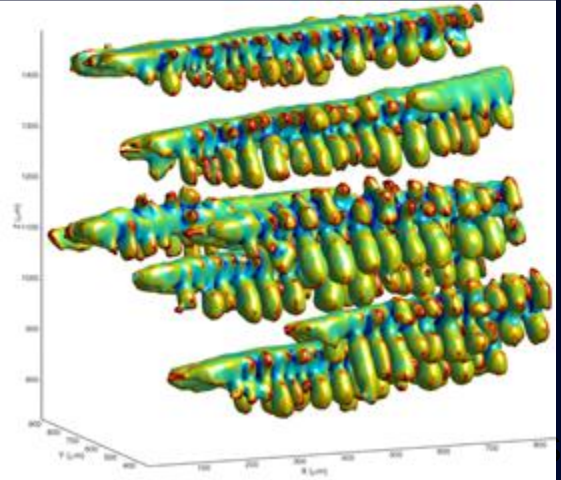


Axial view of interface with corresponding view of interferometric construction.
Pereda, et. al., Phys Rev E, 102.3, 32804.

Directional Solidification – Metal Alloy systems

- **The Solidification Using a Baffle in Sealed Ampoules (SUBSA) hardware is a furnace that can heat samples up to 850°C for a variety of materials science experiments, and there are currently 3 NASA-funded Investigators with upcoming SUBSA experiments:**

- **Dusan Sekulic, University of Kentucky**
  - Objective: Better understand processing kinetics (enhanced wetting, spreading, capillarity) of brazing in low-g environments.
- **Christoph Beckermann, University of Iowa**
  - Objective: Improve the understanding of the columnar-to-equiaxed transition (CET) during solidification of metal alloys.
- **Peter Voorhees, Northwestern University**
  - **Objective: Given the importance of dendrite fragmentation on the presence and location of a CET, examine the roles of melting and capillarity induced pinching on dendrite arm fragmentation, retraction and coalescence during cooling.**



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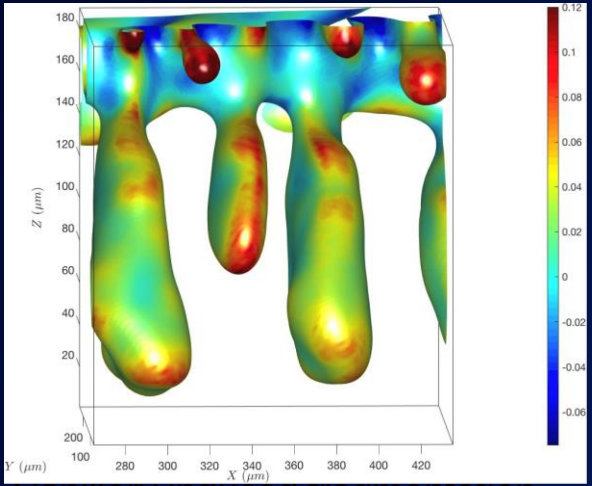


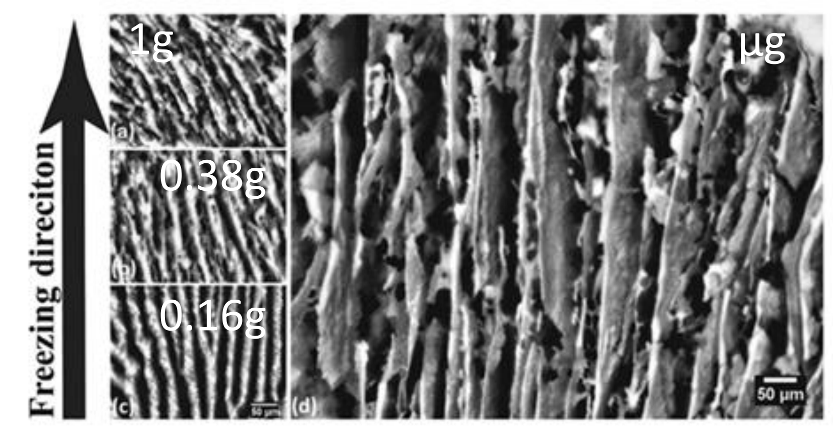
Capillary induced fragmentation

Solidification – Freeze Casting

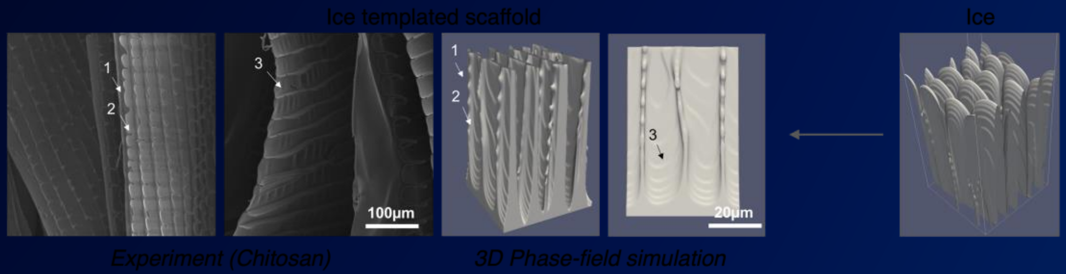
- **The Pore Formation and Mobility Investigation (PFMI) hardware will melt samples of a transparent modeling material, e.g. succinonitrile and succinonitrile water mixtures. There are currently 2 Investigators with upcoming PFMI experiments:**

- **David Dunand, Northwestern University**
    - Objective: Improve understanding of solidification behavior of freeze cast materials, which will allow for the development of improved processing techniques.
    - Potential applications include high strength, low weight materials.

- **Ulrike Wegst, Northeastern University**
    - Objective: Investigate the underlying physics of forming complex scaffolds using the freeze casting methodology.
    - Potential applications include lightweight structural materials as well as scaffolds for peripheral nerve repair.



Dunand: Longitudinal cross-sections of sintered TiO_2 samples sintered from 20 wt% TiO_2 aqueous suspensions directionally solidified under (a) terrestrial, (b) Martian, (c) lunar, and (d) microgravity conditions.



Wegst: Features of freeze-cast templated structures captured by both experiment and 3D phase-field simulation. The salient features include the formation of **lamellae** (1), **undulated ridges** (2) and **wrinkled cell walls** (3).

Ji et al. (2019) MRS Fall Meeting 2019, 1-6 December, Boston, MA, USA

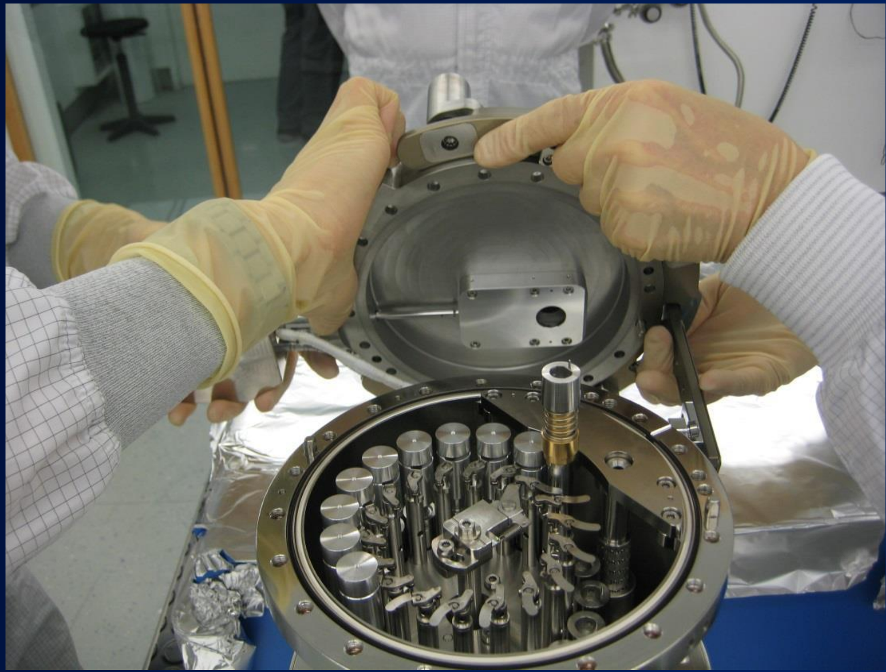
Future Opportunities – Materials Science

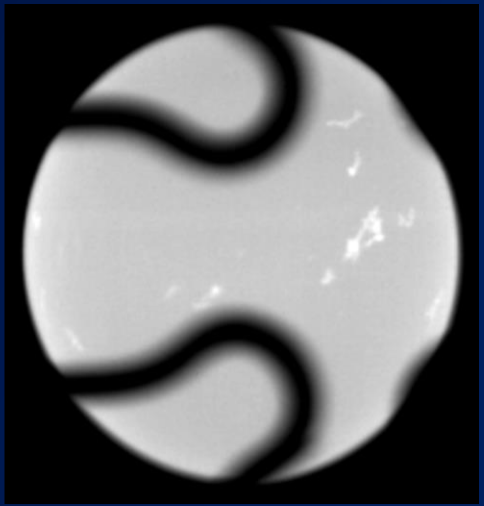
Fundamental – Thermophysical Properties
Non-Equilibrium Phenomena
Integrated Computational Materials Engineering

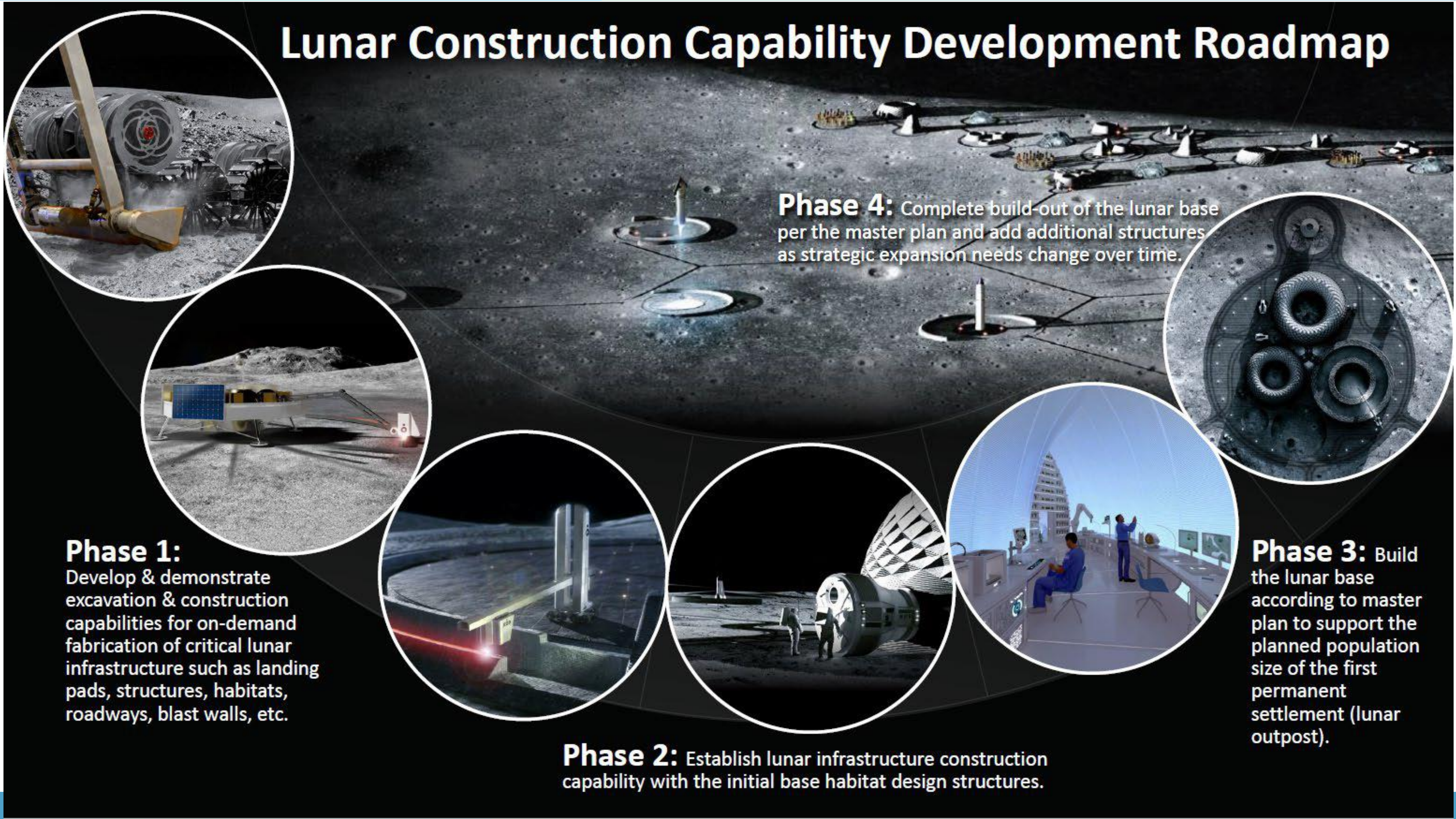
Exploration – Lunar Construction/ISRU
In Space Manufacturing and Repair
Integrated Computational Materials Engineering
Thermophysical Properties

EML Batch 5

- **Objective:** Continue US involvement in ISS-EML experiments. Research in thermophysical properties, fundamental or applicable to exploration.
- **Approach:** utilize ESA ISS-EML
- **Application:**
  - Accurate thermophysical properties are necessary for models used to speed the discovery and development of materials and processes.
    - Applications include manufacturing on the Moon, Mars, and on Earth.
- **Experimental Justification:**
  - For the continued improvement of materials processing, with increasing requirements on chemical composition, microstructure and behavior in use, the reliable and accurate knowledge of the relevant thermophysical properties of high-temperature melts is necessary.
  - Understanding of the physical phenomena involved, from alloy thermodynamics, heat and mass transfers, to solid-liquid interface dynamics, macro- and microstructure and defect formation.





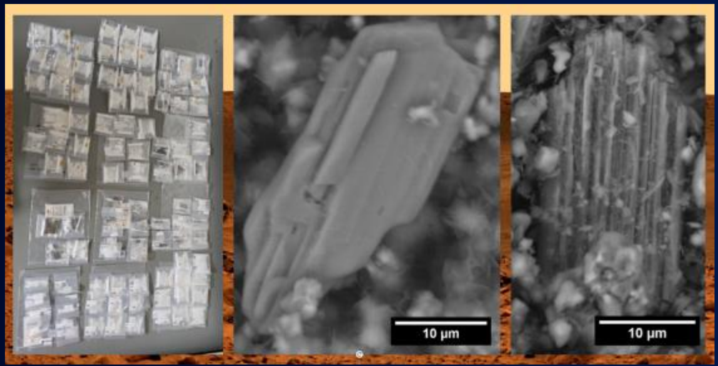

Lunar Construction Capability Development Roadmap
Phase 4: Complete build-out of the lunar base per the master plan and add additional structures as strategic expansion needs change over time.
Phase 1: Develop & demonstrate excavation & construction capabilities for on-demand fabrication of critical lunar infrastructure such as landing pads, structures, habitats, roadways, blast walls, etc.
Phase 2: Establish lunar infrastructure construction capability with the initial base habitat design structures.
Phase 3: Build the lunar base according to master plan to support the planned population size of the first permanent settlement (lunar outpost).

Concrete on the Moon – using Lunar Regolith

- Experiment under consideration as part of the Artemis III astronaut mission
- **Objective:** Analyze the microstructure in regolith-based materials produced in the reduced gravity of the lunar surface.
  - Hardened material would then be brought back to Earth and its mechanical properties evaluated.
- **Approach:** Conduct experiment on the Moon.
  - The astronauts will obtain a small sample of lunar regolith that will be mixed with binder. Some binders will require heat for sample curing.
    - 3 different binders are being considered.
- **Application:**
  - In-situ resources can be effectively used to develop, deliver, and demonstrate on-demand infrastructure to sustain a prolonged presence on the Moon, such as landing pads, habitats, shelters, roadways, berms, and blast shields.

BPS Research
Related to Lunar Surface Construction
applicable to MANU-1095

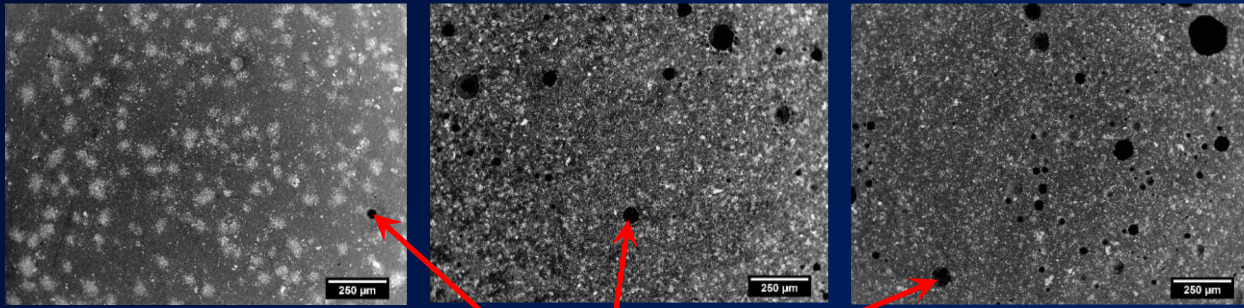
- **Title:** Microgravity Investigation of Cement Solidification (MICS)
- **PI:** Dr. Aleksandra Radlinska, Penn State
- **Objective:** Investigate how microgravity influences the hydration of cementitious systems (Portland cement).
- **Results:**
  - As the gravity level decreased the amount of trapped air and porosity in the samples increased
  - Cement's solidification reaction and resultant microstructure is dependent on the level of gravity.
  - Crystals tend to grow larger in microgravity and they grow in a different orientation.
  - The results indicate that cement solidified in the reduced gravity environment will have different structural and strength properties from 1g.
- **Potential Technology Impacts:** Lunar berms, landing pads, roads



1g μg

The images on the right show gypsum crystal from samples in 1g and μg. The μg crystal shows how minimized fluid convection and a diffusion-controlled hydration process promote a nonuniform microstructure in microgravity.

Astronaut Alexander Gerst conducting the MICS experiment on the ISS



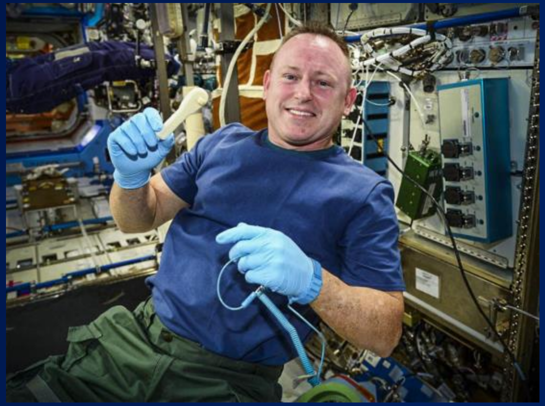
1g 0.17g (Lunar) μg

Trapped air

Materials Science

In-Space Manufacturing

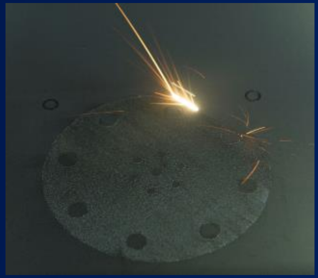
- “The need for a deeper understanding of nonequilibrium phenomena is nowhere greater than in materials science” [1].
  - Materials made by either nature or manufacturing are rarely the result of equilibrium processes.
  - Advanced manufacturing processes, such as additive manufacturing (AM), present new challenges and opportunities for using and understanding nonequilibrium processes.
  - Materials out of equilibrium, such as metallic glasses and high entropy alloys, also present new challenges and opportunities
- Investigating the extreme temperature, solvent, or stress gradients imposed by AM processing provides insight into non-equilibrium reactions and the properties of the metastable materials they produce.
- Furthermore, the capability to fabricate spare parts, replacement units, specialty tools in situ does not exist beyond small demonstration components fabricated from polymers.
- In order to develop and optimize advanced manufacturing processes and enable functionalities such as autonomous self-correction during fabrication, one element that still needs to be understood is how specific materials and material systems behave under the processing and usage conditions.
  - On-orbit, this may mean adjustments due to a lack of buoyancy driven convection or other detectable differences in the thermal environment.
  - For example, in metal additive manufacturing utilizing bound metal deposition, the non-linear shrinkage of parts is affected by gravity.



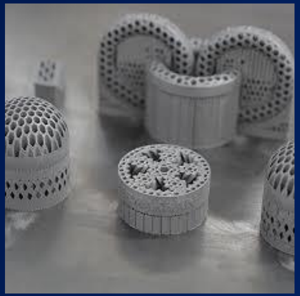
1. National Academies of Sciences, Engineering, and Medicine 2019. Frontiers ofMaterials Research: A Decadal Survey. Washington, DC: The National AcademiesPress. https://doi.org/10.17226/25244

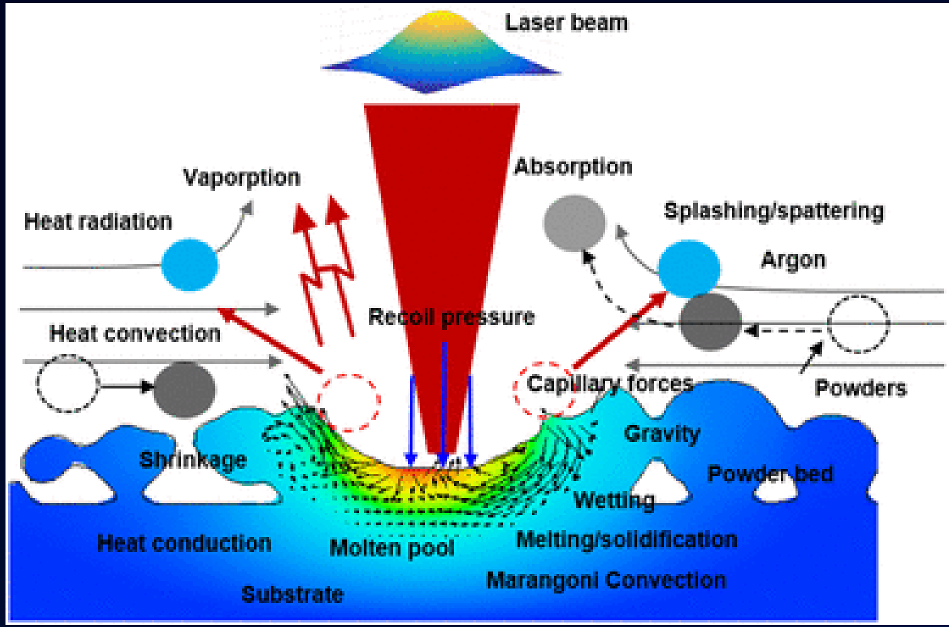
Materials Science – In-Space Manufacturing (con'd)

- A reduced gravity environment inhibits masking phenomena such as buoyancy driven convection and sedimentation to perform experiments targeted to address gaps in fundamental understanding of the underlying physics of materials science.
- Coupling key benchmark experiments with rapidly evolving multiscale modeling (micro, meso, and macro) techniques provides significant insights into underlying physics of microstructure formation and evolution during solidification processes in reduced gravity.
- Understanding the underlying physics during solidification, as the departure from equilibrium increases, is a gap in knowledge that has potential to be fundamentally transformative.
- For example, both terrestrial and in-space manufacturing techniques, such as additive manufacturing techniques such as Selective Laser Melting (SLM), Direct Energy Deposition (DED), Bound Metal Deposition, as well as high-speed processing techniques in glass forming systems.

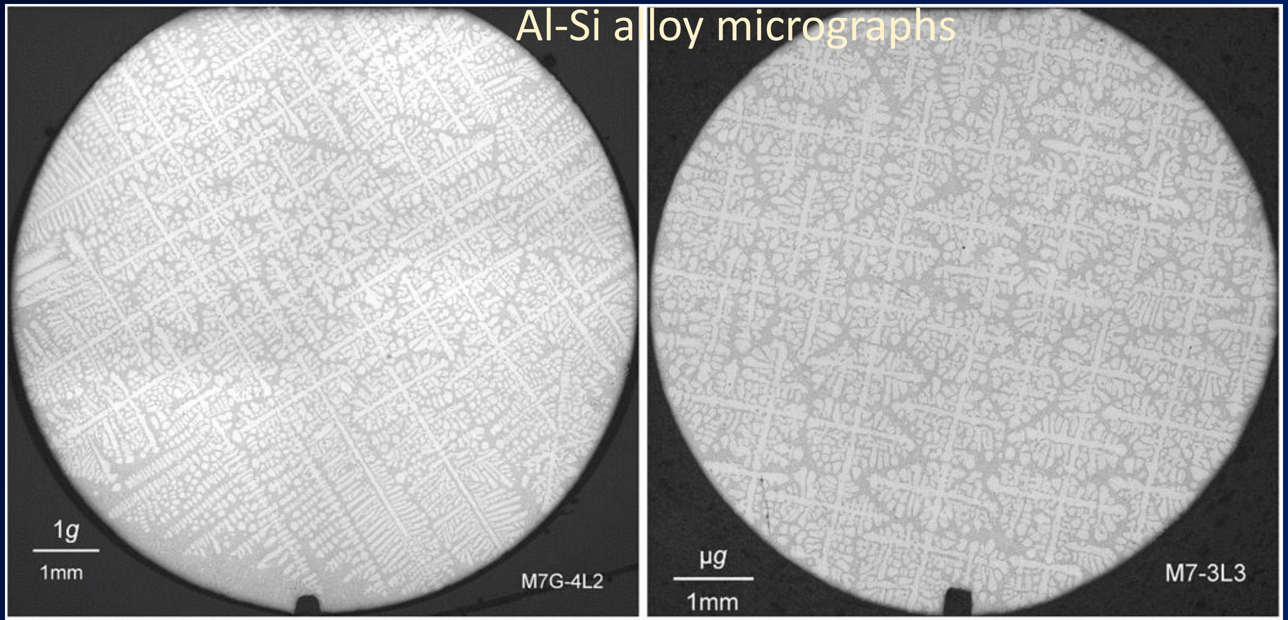


Selective laser melting of a part.





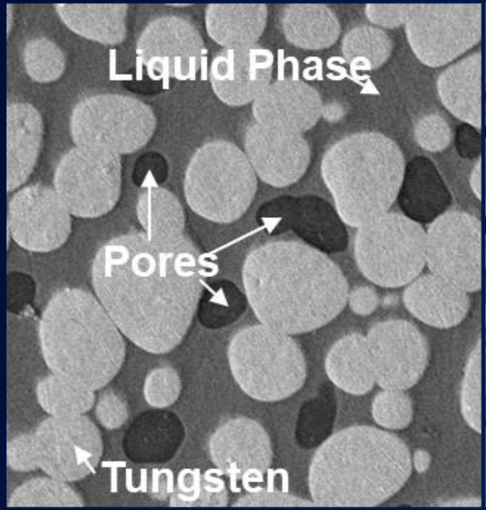
Al-Si alloy micrographs



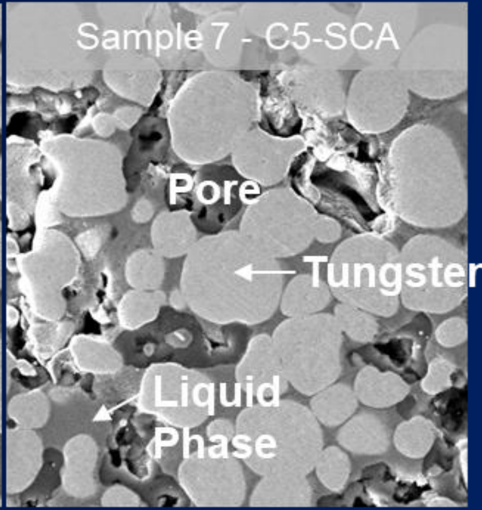
BPS Research: Lunar Surface Manufacturing and Repair

applicable to MANU-644

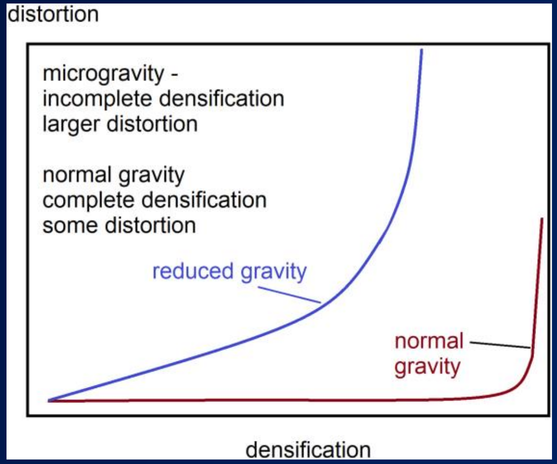
- **Title:** Gravitational Effects on Distortion and Sintering (GEDS)
- **PI:** Dr. Rand German, San Diego State University
- **Objective:** GEDS has three critical goals: (i) the in-depth analysis of the liquid phase sintering-induced pore-grain structure evolution, (ii) understating gravitational effects on distortion during sintering and, (iii) exploring sintering under microgravity conditions as a promising technique for in-space fabrication and repair.
- **Results:** Removal of gravity results in pore coalescence, loss of skeletal rigidity, and distortion without full densification.
- The results indicate that parts sintered in microgravity may have decreased strength due to limited pore migration/push out to the surface.
- **Potential Technology Impacts:** additive manufacturing



1g



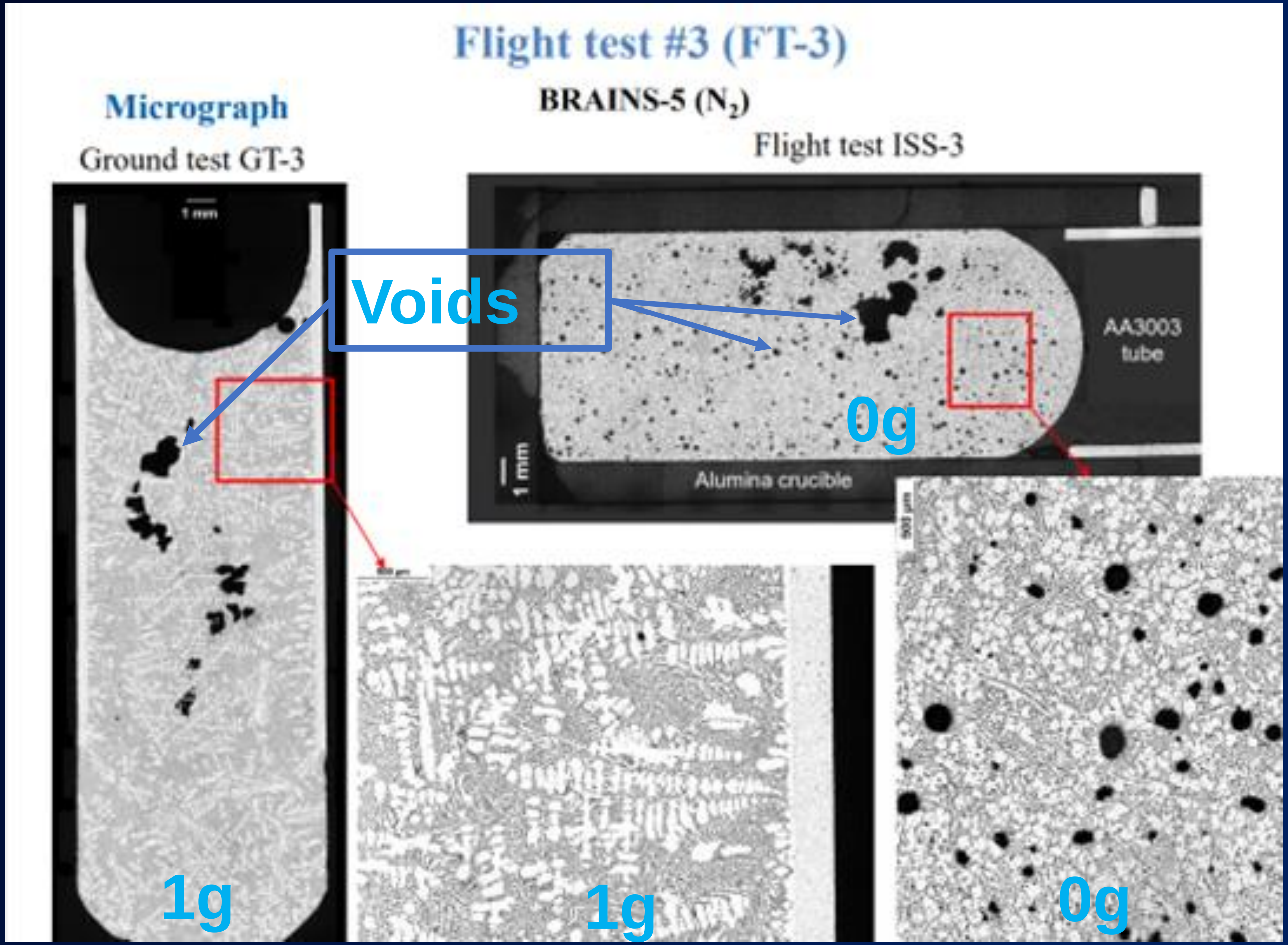
μg



Sintering in microgravity results in more distortion and less densification.

BPS Research: Welding in Space
applicable to MANU-646

- **Title:** BRazing of Aluminum Alloys IN Space (BRAINS)
- **PI:** Dr. Dusan Sekulic, Univ. of Kentucky
- **Objective:** Increase understanding of processing kinetics during brazing in µg
- **Results:** Validated model of braze behavior. Provided results informing many aspects of practical braze joint design including flow distances, porosity/microstructure formation, surface clad behaviors, mechanisms of added and imbedded fluxes. Larger number of voids and greater distribution in microgravity. Al-Si alloy.
- **Potential Technology Impacts:** space welding and brazing, In-space Servicing, Assembly, and Manufacturing (ISAM)



Distributed porosity and round α phase in microgravity ISS sample vs typical dendritic formation in ground sample

New Mid- Temperature Furnace for CLD

NASA ISS- PO to develop a furnace with the following capabilities.

- Tentative Capabilities:
  - Temperature: 1250 C,
  - Sample translation,
  - Heated zones
  - 16 mm sample diameter (vs 12mm on current SUBSA).

➢ Use on ISS and then transfer to Commercial Space Stations

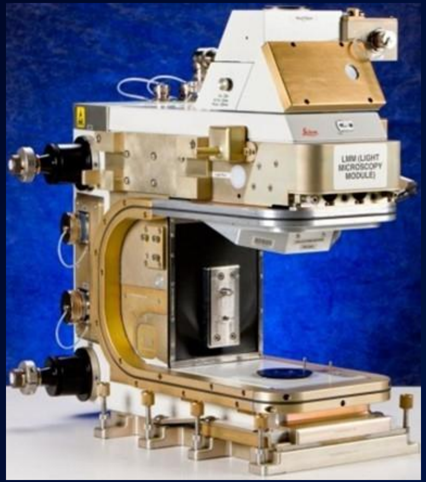
➢ ISS PO to release a Request for Information (RFI) – receive recommendations from Science community for additional capabilities.

Soft Matter

ACE Series – Approach: ISS Instrumentation

Light Microscopy Module (LMM): High-resolution confocal microscope

Sample Module



3D Microscope

Fluids Integrated Rack

Advanced Colloids Experiments – Temperature Controlled (ACE-T)

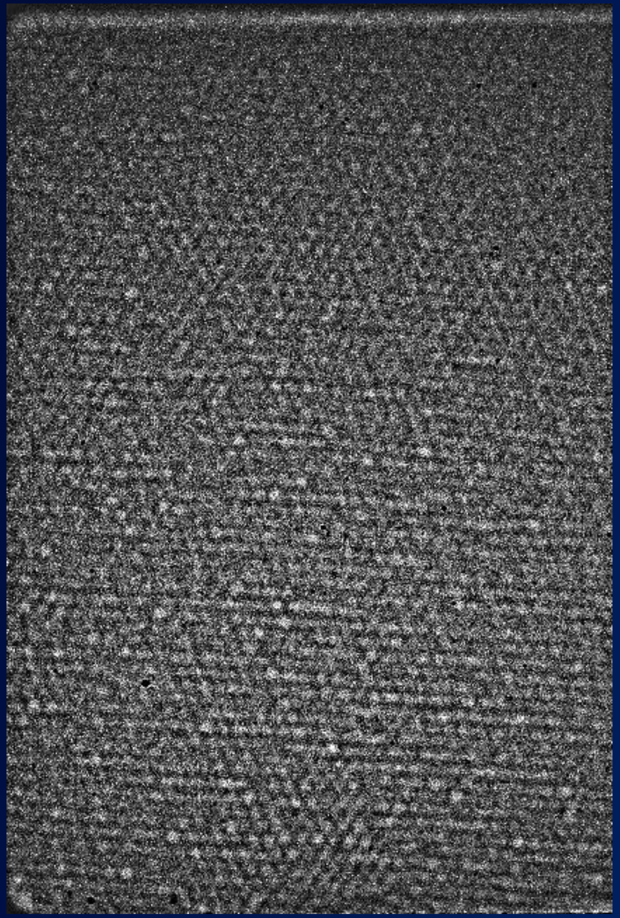
Objectives: Obtain phase diagrams as a function of temperature, particle concentration and geometry.

ACE-T4, PI: Arjun Yodh, University of Pennsylvania
- Focus: Effect of polydispersity

ACE-T7, PI: Paul Chaikin, New York University
- Focus: Determine Phase Diagram for Cubes

ACE-T11, PI: Boris Khusid, New Jersey Institute of Technology
Pul Chaikin, New York Iniversity
- Focus: Determine Phase Diagram for Spheres

ACE-TR-1, PI: Boris Khusid, New Jersey Institute of Technology
Paul Chaikin, Andrew Hollingsworth New York Univ.
- Focus: Determine Phase Diagram for Ellipsoids



ACE –T11: Large Defect-Free FCC Crystal, like nothing seen on Earth, created on ISS – confirms 50-year-old theory.

Advanced Colloids Experiments – Temperature Controlled (ACE-T) (con'd)

ACE-T5, PI: Ali Mohraz, University of California, Irvine

- **Objective: Quantify the theory behind creating large surface area electrodes using bigels**

ACE-T6, PI: Matt Lynch, Proctor and Gamble

- **Objective: Examine shelf life stability as a function of temperature.**

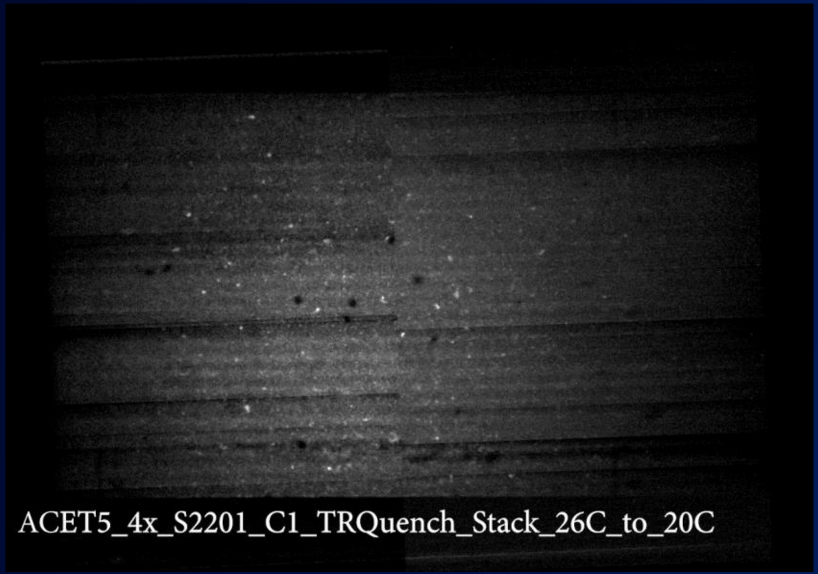
ACE-T9, PI: David Marr, Colorado School of Mines

- **Objective: Assembling colloidal structures using magnetic fields.**

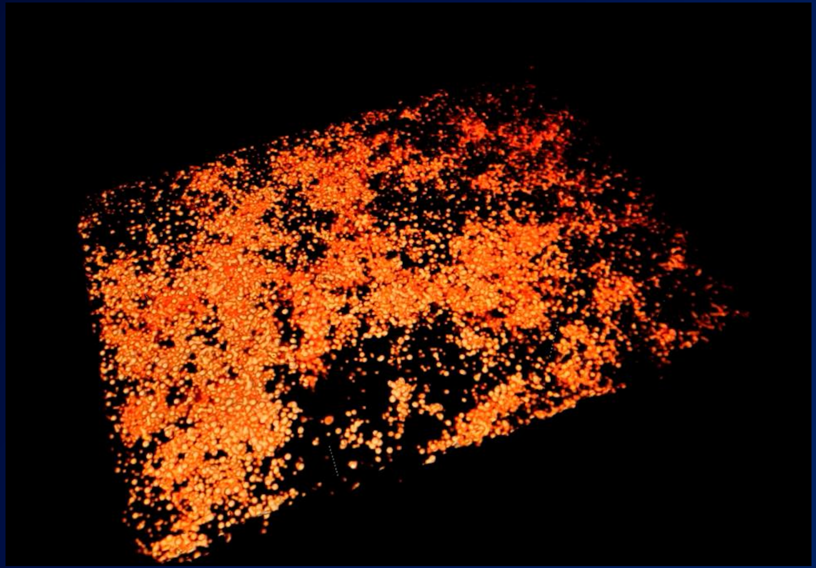
ACE-T12, PI: Stuart Williams, University of Louisville

- **Objective: Study Nano-particle Haloing**

ACE-T5

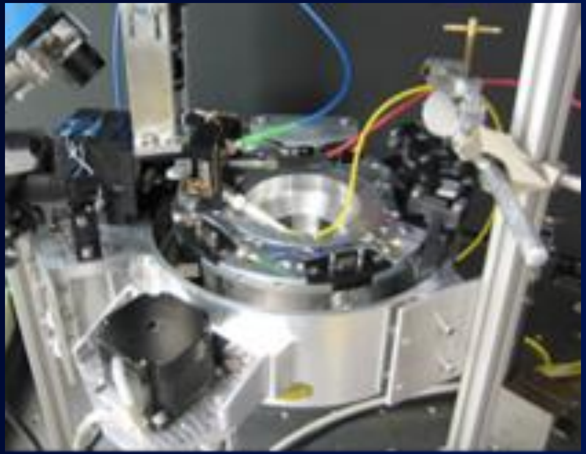


ACE-T6



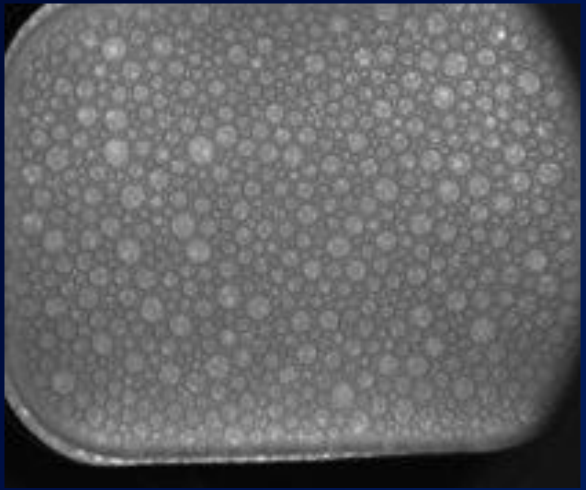
Foam Optics And Mechanics (FOAM) - ISS

- ESA Team Coordinator : Professor Dominique Langevin (University of Paris, France)
- US PI: Douglas Durian, Physics Department, University of Pennsylvania
- Team: D. Weaire (Ireland); Nicolas Vandewalle, Hérvé Caps, Giles Delon (Belgium); Ko Okamura (Japan); Andrei Sonin (Russia)



ESA - FOAM C Hardware, ISS Image

- Objectives:
- To exploit microgravity conditions to quantify and elucidate the unusual elastic character of foam structure and dynamics.
- To observe how the foam melts into a simple viscous liquid as a function of both increasing liquid content and shear strain rate.
- The flight research generates valuable fundamental guidance for the development of foam materials with more desirable rheology and better stability.



FOAM C Image from ISS

Liquid Crystal Film Experiment - ISS

Title: STUDY OF STRUCTURES & DYNAMICS OF IINCLUSIONS ON 2 DIMENSIONAL FREELY SUSPENDED SMECTIC LIQUID CRYSTAL FILMS IN MICROGRAVITY

Investigator team:
Thailand – PI Prof. Chattam and Co –I Prof. Pattanaporkratana; Kasetsart University; Co-I Natthawat Hongkarnjanakul, Engineer, Geo-Informatics and Space Technology Development Agency (Gistda)
NASA sponsored – TBD, via solicitation

Objectives:

- Using ISS KERMIT microscope, investigate liquid crystal film defects (island) and the effects of Lehmann rotation in microgravity. To study Lehmann effect (continuous rotation of liquid crystal droplets subjected to a temperature gradient) and Marangoni effect on smectic island of freely suspended film by heating the film or creating partial pressure across the film (i.e. to have a small confined enclosure on either side of film) and study rotation mechanism of the island.

Collaboration Approach:

- Flight hardware development – Kasetsart University, Thailand Government
- Guidance during hardware development - NASA BPS and ISS-PO
- ISS, launch, integration and ops – NASA ISS-PO and BPS

Drawings by Lehmann of droplet textures that wind and rotate under the action of an increasing temperature gradient*

Status:

- ✓ KU proposal and draft schedule – completed,
- International Agreement – Original agreement to be revised
- Flight hardware development - 2023 – 24, ISS ops – 2025

*Lehmann O. Structur, System und magnetisches Verhalten flüssiger Krystalle und deren Mischbarkeit mit festen. Ann Phys. 1900;307:649–705

Future Opportunities – Soft Matter/Complex Fluids

- Non- Equilibrium systems
- Non- Newtonian fluid systems

- Colloids, Gels
- Granular Materials
- Foams, Emulsions
- Dusty Plasmas

Soft Matter Mini-Workshops— Science Questions

- **Colloidal Science**
  - Impact of particle shape, anisotropicity, functionality, external stimuli on colloidal assembly.
  - Impact of gravity on 3D printing of colloidal particles
- **Non-Newtonian Fluids**
  - Fundamental understanding of rheology by understanding impact of interparticle forces and gravity
  - Motility of active matter
  - Non-Newtonian nature of network flow
- **Granular Media**
  - Generalizability of phenomenological models for granular media
  - Effect of charging on granular media flow
  - Fundamental understanding of flow regime change, impact of gravity and interaction force between individual particles

Mini-Workshops - High Level Summary

- The community is eager for NASA to push the envelop of fundamentals of soft matter science in reduced- and micro-gravity science.
- Participants appreciated the event and enthusiastically participated during the mini-workshops. They also send their additional feedback after the events. The event generated many “shovel ready” ideas.
- The modularity of experimental hardware and availability of modular diagnostic capabilities were identified as key asks across forums.
- AI/ML was identified as a key component via multiple avenues for application ranging from using it as a tool for improved analytics of data and images to developing theories for fundamental science (e.g.- Physically Interpretable Neural Network).
- Community wants more interaction with other domains of space science to understand the challenges with other domain of space science, biological sciences and other domains of science.

Soft Matter Dynamics Unit
to remain on ISS for several years

Areas of interest
- *Foams*
- *Emulsions*
- *Colloids*
- *Gels*
- *Granular Materials*

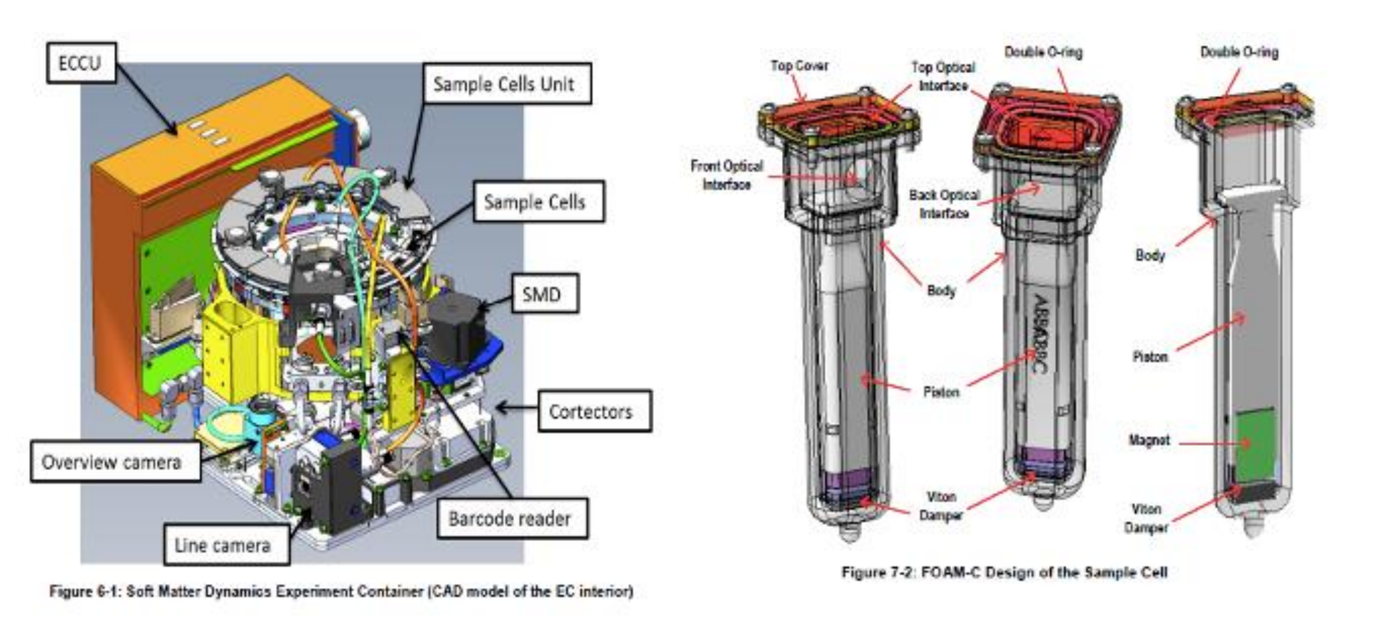


Figure 6-1: Soft Matter Dynamics Experiment Container (CAD model of the EC interior)
Figure 7-2: FOAM-C Design of the Sample Cell

Soft Matter Dynamics Unit

Soft Matter/Complex Fluids

Objective:

- Obtain short duration microgravity data at a ground-based research facility:
  - Identify phenomena that are obscured by buoyancy and other effects (e.g.- electrostatic charge, phase separation) that may alter anticipated behavior.
  - Explore and refine test matrices for space flight experiments.
- Demonstrate hardware and experiment feasibility.

Approach:

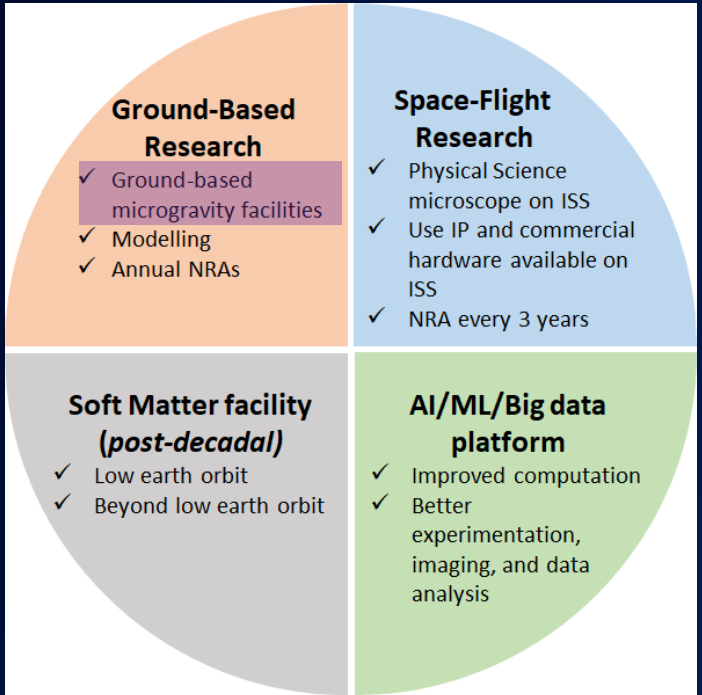
- Integrate high fidelity microscopy inline with requirements outlined in the "Grand Challenge" workshop:
  - Traditional Microscopy (transmission, reflection mode, immersion optics etc.)
  - Nipkow Disc Confocal Microscopy
  - Laser Tweezers
  - Ability to add external stimuli (e.g.- temperature gradient, magnetic field, electric field etc.)
- Utilize elongation rheometers to characterize properties and behavior of soft matter
- Develop inline high speed characterization capabilities:
  - Impedance spectroscopy
  - Voltametry

Relevance/Impact:

- Alignment with the "Grand Challenge" workshop report for soft matter.
- Provide capability to down select for flight programs.

Implementation Approach:

- Advertise ground-based low gravity capabilities to PIs in NRAs.
- Project scientists to serve as interface between PIs and facilities.
- Build microscope rigs for both 2.2 Second Drop Tower and Zero G Facility.
- Utilize 2.2 Second Drop Tower standard frame to allow integration of rheometer and other techniques between 2.2 second drop tower and Zero G Facility.
- Hardware Refresh: *Every three years*, reevaluate instrumentation specifications and capabilities and update as necessary.



Implementation plan

ISS or CLD Microscope Development


Thank you!